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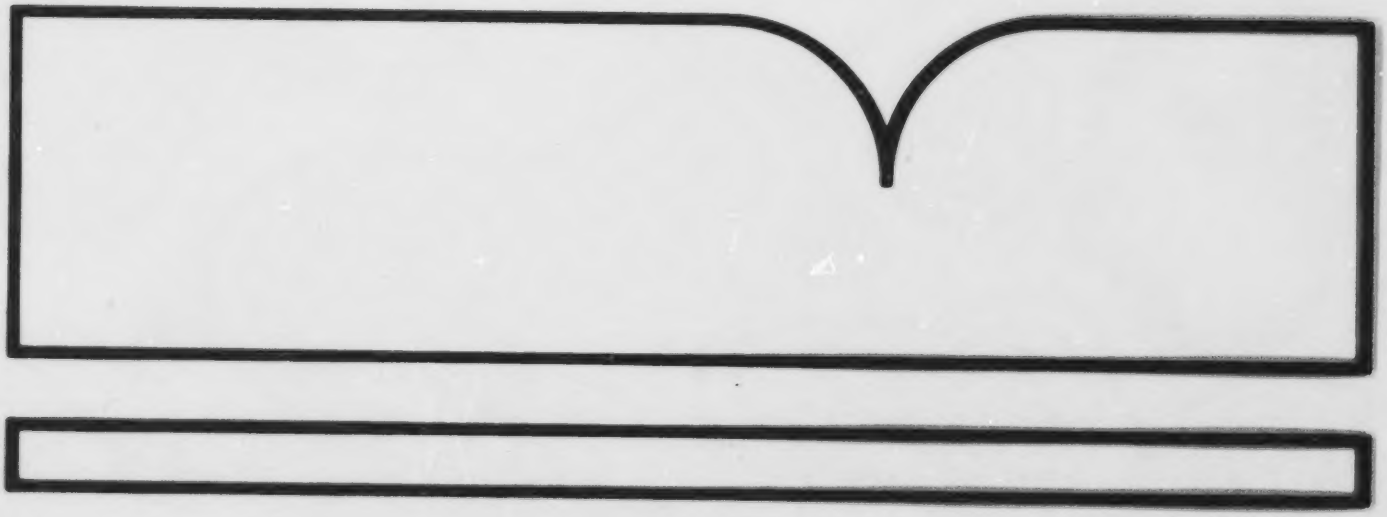

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This ambient water quality criteria document reviews the aquatic toxicity data available for selenium. Pertinant high quality studies are selected, and the toxic effects of selenium on aquatic organisms is discussed. The criteria for fresh water are calculated and formally presented in this document.

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AMBIENT AQUATIC LIFE WATER QUALITY CRITERIA FOR

SELENIUM

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF RESEARCH AND DEVELOPMENT
ENVIRONMENTAL RESEARCH LABORATORIES
DULUTH, MINNESOTA
NARRAGANSETT, RHODE ISLAND

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FOREWORD

Section 304(a)(1) of the Clean Water Act of 1977 (P.L. 95-217) requires the Administrator of the Environmental Protection Agency to publish water quality criteria that accurately reflect the latest scientific knowledge on the kind and extent of all identifiable effects on health and welfare that might be expected from the presence of pollutants in any body of water, including ground water. This document is a revision of proposed criteria based upon consideration of comments received from other Federal agencies, State agencies, special interest groups, and individual scientists. Criteria contained in this document replace any previously published EPA aquatic life criteria for the same pollutant(s).

The term "water quality criteria" is used in two sections of the Clean Water Act, section 304(a)(1) and section 303(c)(2). The term has a different program impact in each section. In section 304, the term represents a non-regulatory, scientific assessment of ecological effects. Criteria presented in this document are such scientific assessments. If water quality criteria associated with specific stream uses are adopted by a State as water quality standards under section 303, they become enforceable maximum acceptable pollutant concentrations in ambient waters within that State. Water quality criteria adopted in State water quality standards could have the same numerical values as criteria developed under section 304. However, in many situations States might want to adjust water quality criteria developed under section 304 to reflect local environmental conditions and human exposure patterns before incorporation into water quality standards. It is not until their adoption as part of State water quality standards that criteria become regulatory.

Guidance to assist States in the modification of criteria presented in this document, in the development of water quality standards, and in other water-related programs of this Agency has been developed by EPA.

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Introduction

Selenium is unique among pollutants because of its following attributes:

1. Selenium is located immediately below sulfur in group 6A in the periodic table. Thus selenium is a metalloid, not a metal. More importantly, the chemical and physical properties of selenium and sulfur are so similar that these elements are related in a variety of ways. For example, selenium can replace sulfur in some minerals and biologically important compounds (Callahan et al. 1979; Cooper et al. 1974; Ewan 1979; Shamberger 1983). Also, sulfate reduces the toxicity of selenium to some species (Bennett et al. 1986; Ewan 1979; Halverson and Monty 1960; Kumar and Prakash 1971; Martin 1973; Sarma and Jayaraman 1984; Shrift 1954a,b,1961; Wheeler et al. 1982). However, if selenium and sulfur were physiologically and toxicologically interchangeable, selenium would not be more toxic than sulfur (Brown and Shrift 1982; Shamberger 1983; Shrift 1973). Some of the proposed modes of action of selenium involve reaction with or substitution for the sulfur in such biologically relevant natural compounds as sulfur-containing amino acids (Foe and Knight, Manuscript; Magos and Webb 1980).
2. Substantial quantities of selenium enter surface waters from both natural and anthropogenic sources. It is abundant in the drier soils of North America from the Great Plains to the Pacific Ocean. Some ground waters in California, Colorado, Kansas, Oklahoma, South Dakota, and Wyoming contain elevated concentrations of selenium due to weathering of and leaching from rocks and soils. Selenium also occurs in sulfide deposits of copper, lead, mercury, silver, and zinc and can be released during the mining and smelting of these ores. In addition, selenium occurs in high concentrations in coal and fuel oil and is emitted in flue gas and in fly

ash during combustion. Some selenium then enters surface waters in drainage from fly-ash ponds and in runoff from fly-ash deposits on land.

3. Three oxidation states (selenide = -2, selenite = +4, and selenate = +6) can exist simultaneously in aerobic surface water at pH = 6.5 to 9.0. A fourth oxidation state (elemental = 0) exists in sediment, but is insoluble in water. Chemical conversion from one oxidation state to another often proceeds at such a slow rate in aerobic surface water that thermodynamic considerations do not determine the relative concentrations of the oxidation states. Thus although selenium(VI) is thermodynamically favored in oxygenated alkaline water, substantial concentrations of both selenium(-II) and selenium(IV) are not uncommon (Burton et al. 1980; Cutter and Bruland 1984; Measures and Burton 1978; North Carolina Department of Natural Resources and Community Development 1986; Robberecht and Van Gricken 1982; Takayanagi and Cossa 1985; Takayanagi and Wong 1984a,b; Uchida 1980).

4. Living organisms can affect selenium in a variety of ways, and Shrift (1964) postulated a selenium cycle in which some species reduce the most oxidized form and others oxidize the reduced form(s). For example, organisms can oxidize elemental selenium to selenium(IV) (Sarathchandra and Watkinson 1981), reduce selenium(VI) to selenium(IV) (Lipinski et al. 1986), produce gaseous dimethyl selenide and dimethyl diselenide (Chau et al. 1976; Doran 1982; Reamer and Zoller 1980), and reduce selenium(IV) and selenium(VI) to selenium(-II) and incorporate it into amino acids and proteins, such as selenomethionine (Bottino et al. 1984; National Research Council 1976; Stadtman 1974; Wrench 1978,1979).

5. Although selenium can be quite toxic, it has been shown to be an essential trace nutrient for many aquatic and terrestrial species and it

ameliorates the effects of a variety of pollutants. Selenium deficiency has been found to affect humans (Fishbein 1984; Frost and Ingvolstad 1975; Raptis et al. 1983; Wilber 1980,1983), sheep and cattle (Shamberger 1983), fish (Bell et al. 1984,1985,1986; Fjolsand and Heyarass 1985; Gatlin 1983; Gatlin and Wilson 1984; Heisinger and Dawson 1983; Hilton et al. 1980; Hodson and Hilton 1983; Ostroumova 1986; Poston et al. 1976; Wilson et al. 1984), an aquatic invertebrate (Cowgill et al. 1985,1986; Keating and Dagbusan 1984), and algae (Lindstrom 1984; Wehr and Brown 1985). In addition, selenium protects biota from the toxic effects of arsenic, cadmium, copper, inorganic and organic mercury, silver, and the herbicide paraquat in both aquatic and terrestrial environments (Beijer and Jernelov 1978; Eisler 1985; Ganther 1980; Heisinger and Scott 1985; Heisinger et al. 1979; Hutchinson and Stokes 1975; Kim et al. 1977; Levander 1977; Magos and Webb 1980; Pelletier 1986b; Shamberger 1983; Skerfving 1978; Van Puymbroeck et al. 1982; Wilber 1983; Winner 1984). Birge et al. (1978,1979a,b,1981) and Huckabee and Griffith (1974), however, reported that selenium and mercury acted synergistically toward fish embryos. Selenium pretreatment protected 128-hr old, but not 6-hr old, embryos of Oryzias latipes from cadmium and mercury (Heisinger 1981), whereas prior exposure to selenium did not affect the sensitivity of white suckers to cadmium (Duncan and Klaverkamp 1983). Selenium is reported to reduce the uptake of mercury by some aquatic species (Klaverkamp et al. 1983; Moharram et al. 1987; Rudd et al. 1980; Turner and Rudd 1983; Turner and Swick 1983), to have no effect on uptake of mercury by a mussel (Pelletier 1986a), and to increase the uptake of mercury by mammals and some fish (Heisinger et al. 1979; Kim et al. 1977; Luten et al. 1980; MacKay et al. 1975; Ringdal and Julshamn 1985; Shultz

and Ito 1979). Selenium augmented accumulation of cadmium in some tissues of the shore crab, Carcinus maenas (Bjerregaard 1982,1985). The available data do not show whether the various inorganic and organic compounds and oxidation states of selenium are equally effective sources of selenium as a trace nutrient or as protection against pollutants.

6. Not only has selenium been demonstrated to be toxic to aquatic species when it is dissolved in water, it has also been demonstrated that uptake of selenium from food can adversely affect aquatic species (e.g., Bennett et al. 1986; Goettl and Davies 1978; Hicks et al. 1984; Hilton et al. 1980; Hodson and Hilton 1983) and mallard ducks (Heinz et al. 1987; Hoffman and Heinz 1987).

7. In some situations aquatic organisms accumulate more selenium from food than from water (Birkner 1978; Fowler and Benayoun 1976a,b,c; Rudd et al. 1980; Sandholm et al. 1973; Turner and Swick 1983). Turner and Swick (1983) also found that under some conditions pike accumulated equal amounts from food and water. Shrimp lost selenium that had been accumulated from water faster than that accumulated from food (Fowler and Benayoun 1976a).

8. Selenium(-II) as selenomethionine is sometimes more biologically active than either selenium(IV) or selenium(VI). Fish accumulated selenomethionine more efficiently than selenium(IV) or selenium(VI) from both the gastrointestinal tract (Kleinow 1984; Kleinow and Brooks 1986a) and from water (Sharma and Davis 1980). Sandholm et al. (1973) found that algae accumulated selenomethionine much more than selenium(IV), but the opposite was true for daphnids and fish. Also, Kumar and Prakash (1971) and Niimi and LaHam (1976) reported that selenium as selenomethionine was more toxic to algae and fish, respectively, than

were selenium(IV) and selenium(VI). Selenopurine was as toxic to algae as selenomethionine (Kumar and Prakash 1971), but selenocystine was less toxic to fish (Niimi and LaHam 1976). Heinz et al. (1987) and Hoffman and Heinz (1987) found that selenium as selenomethionine is more toxic to mallards than selenium(IV) and that mallards contained more selenium in eggs, liver, and breast muscle when fed selenomethionine than when fed selenium(IV).

9. The concentration of selenium in specific tissues can depend on the exposure route, concentration, and form of selenium. For example, Lemly (1982) found relatively low concentrations of selenium in gonads of centrarchids exposed to selenium(IV) in laboratory tests, whereas Cumbie and Van Horn (1978) found high concentrations in gonads of centrarchids from Belews Lake, which contained a moderately high concentration of selenium. In another case, at low levels of selenium(IV) in food or water, the kidneys of rainbow trout contained more selenium than the livers, whereas the converse was true at higher concentrations (Hilton et al. 1982; Hodson and Hilton 1983; Hodson et al. 1980). Similarly, the relative distribution of selenium in tissues of shrimp depended on whether the selenium was accumulated from water or from food (Fowler and Benayoun 1976b). Also, Heinz et al. (1987) found that when mallards were fed selenium(IV), more selenium was deposited in the egg yolk than in the egg white. When mallards were fed selenomethonine, however, more selenium was found in the white than in the yolk. In addition, the relative distribution between tissues might depend on the duration of the exposure and on whether the organisms are in the uptake or depuration phase (Kleinow and Brooks 1986a).

10. Selenium occurs in a variety of forms in organisms. Because of "alkali disease" and "blind staggers" among livestock, the characterization of selenium in terrestrial plants has received much attention. The water-soluble fraction from plants contained selenite, selenate, seleno-amino acids, and possibly other compounds. After treatment of the insoluble fraction with proteolytic enzymes, various seleno-amino acids were found (Allaway et al. 1967; Brown and Shrift 1982; Olson et al. 1970). Selenium in algae has been found in free and combined amino acids (Bottino et al. 1984; Burton et al. 1980; Wrench 1978) and bound to lipids (Gennity et al. 1984). Similarly, saltwater animals contained selenium in proteins and lipids (Braddon-Galloway and Sumpter 1986; Lunde 1973; Maher 1985; Wrench 1979). Cappon (1984) and Cappon and Smith (1981,1982a,b) found that 8 to 47% of the selenium in the edible portions of various freshwater and saltwater species was selenium(VI) and that 35 to 80% was water-soluble.

Although other pollutants possess some of these attributes, selenium is the only pollutant for which all of these have been demonstrated. Many of these attributes make it difficult to design and conduct tests on selenium and to decide how the data should be interpreted and used to derive aquatic life water quality criteria for selenium. On the other hand, comparison of the form and location of selenium in affected and unaffected organisms from laboratory and field exposures might be helpful in determining the route by which aquatic organisms in field situations accumulate toxic amounts of selenium.

Unless otherwise noted, all concentrations of selenium in water reported herein from toxicity and bioconcentration tests are expected to be essentially equivalent to acid-soluble selenium concentrations. All concentrations are

expressed as selenium, not as the chemical tested. Although VI is expected to be the predominant oxidation state at chemical equilibrium in oxygenated alkaline water, the rate of conversion of IV to VI seems to be slow in most natural waters. Therefore, it was assumed that when IV was introduced into stock or test solutions, it would persist as the predominate state throughout the test, even if no analyses specific for the IV oxidation state were performed. Similarily, it was assumed that when VI was introduced into stock or test solutions, it would persist as the predominant state throughout the test, even if no analyses specific for VI were performed.

An understanding of the "Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses" (Stephan et al. 1985), hereinafter referred to as the Guidelines, and the response to public comments (U.S. EPA 1985a) is necessary in order to understand the following text, tables, and calculations. Results of such intermediate calculations as recalculated LC50s and Species Mean Acute Values are given to four significant figures to prevent roundoff error in subsequent calculations, not to reflect the precision of the value. The criteria presented herein supersede previous national aquatic life water quality criteria for selenium (U.S. EPA 1976,1980a) because these new criteria were derived using improved procedures and additional information. The latest comprehensive literature search for information for this document was conducted in July, 1986; some more recent information was included.

Acute Toxicity to Aquatic Animals

Selenium(IV)

Data that may be used, according to the Guidelines, in the derivation of Final Acute Values for selenium(IV) and selenium(VI) are presented in Table

1. The LC50 for selenium(IV) sometimes decreased substantially as the duration of the test increased. For example, Halter et al. (1980) reported the LC50 for the amphipod, Hyalella azteca, to be 940 µg/L at 2 days, 340 µg/L at 4 days, and 70 µg/L at 14 days. (Although Halter et al. (1980) did not specify the oxidation state used in their studies, Adams and Johnson (1981) stated that the tests were conducted on sodium selenite.) Similarly, Adams (1976) reported that the average LC50 for the rainbow trout, Salmo gairdneri, was 4,350 µg/L at 4 days, 500 µg/L at 48 days, and 280 µg/L at 96 days, and for the fathead minnow, Pimephales promelas, the average LC50 was 10,900 µg/L at 4 days and 1,100 at 48 days.

Adams (1976) found that the acute toxicity of selenium(IV) to the fathead minnow was related to water temperature with average 96-hr LC50s of 10,900 µg/L at 13°C, 6,700 µg/L at 20°C, and 2,800 µg/L at 25°C. A daphnid, a midge, and the striped bass, Morone saxatilis were more sensitive to selenium(IV) in soft than in hard water (Mayer and Ellersieck 1986; Palawski et al. 1985). These results might be explained by the findings of Lemly (1982) that both temperature and hardness influenced the rate of uptake of selenium by centrarchids in short exposures, but that neither temperature nor hardness had a significant effect on the final concentration in any tissue after exposure to selenium(IV) for 120 days.

Invertebrates are both the most sensitive and most resistant freshwater species to selenium(IV) with acute values ranging from 210 µg/L for the crustacean, Daphnia magna (Adams and Heidolph 1985) to 203,000 µg/L for the leech, Nephelopsis obscura (Brooke et al. 1985). The acute values for fishes range from 620 µg/L for the fathead minnow (Kimball, Manuscript) to 35,000 µg/L for the common carp, Cyprinus carpio (Sato et al. 1980).

Boyum (1984) reported a 48-hr LC50 of 6 μg/L for Daphnia pulicaria. Other acute values reported for species in the genus Daphnia ranged from 210 μg/L (Adams and Heidolph 1985) to 3,870 μg/L (Reading 1979; Reading and Buikema 1983), so the value of 6 μg/L is surprisingly low. Boyum (personal communication, 14 February 1986) stated that the survival of Daphnia pulicaria in the lowest concentration tested was only 47% in the test that produced the LC50 of 6 μg/L. Because of the high mortality at the lowest concentration, the value of 6 μg/L was not considered acceptable for use in calculating a criterion. However, the results of this and similar unreported tests by Boyum (personal communication, 14 February 1986) indicate that the acute value for this species might be less than 100 μg/L.

Just as the nine acute values for Daphnia magna cover a rather large range from 210 to 2,500 μg/L, the acute values for the fathead minnow range from 620 to 11,300 μg/L. The values reported by Kimball (Manuscript) were the lowest for the fathead minnow, but not for Daphnia magna. The seven acute values for the rainbow trout range from 1,800 to 12,500 μg/L.

Freshwater Species Mean Acute Values (Table 1) were calculated as geometric means of the available acute values for selenium(IV), and Genus Mean Acute Values (Table 3) were then calculated as geometric means of the Species Mean Acute Values. Of the twenty-two genera for which freshwater mean acute values are available, the most sensitive genus, Hyalella, is 597 times more sensitive than the most resistant, Nephelopsis. The range of sensitivities of the four most sensitive genera is a factor of 5. The freshwater Final Acute Value for selenium(IV) was calculated to be 371.8 μg/L using the procedure described in the Guidelines and the Genus Mean Acute Values in Table 3. The Final Acute Value is higher than the lowest Species Mean Acute Value.

Acute toxicity data that can be used to derive a saltwater criterion for selenium(IV) are available for eight species of invertebrates and eight species of fish that are resident in North America (Table 1). The range of acute values for saltwater invertebrates extends from 850 μg/L for adults of the copepod, Acartia tonsa (Lussier 1986) to greater than 10,000 μg/L for embryos of the blue mussel, Mytilus edulis (Martin et al. 1981) and embryos of the Pacific oyster, Crassostrea gigas (Glickstein 1978; Martin et al. 1981). The range of acute values for fish is slightly wider than that for invertebrates, extending from 599 μg/L for larvae of the haddock, Melanogrammus aeglefinus, to 17,350 μg/L for adults of the fourspine stickleback, Apeltes quadracus (Cardin 1986). No consistent relationship was detected between life stage of invertebrates or fish and their sensitivity to selenium(IV), and few data are available concerning the influence of temperature or salinity on the toxicity of selenium(IV) to saltwater animals. Acute tests with the copepod, Acartia tonsa, at 5 and 10°C gave similar results (Lussier 1986).

Of the fifteen genera for which saltwater mean acute values are available (Table 3), the most sensitive genus, Melanogrammus, is nearly 29 times more sensitive than the most resistant, Apeltes. The sensitivities of the four most sensitive genera differ by a factor of only 2.1, and these four include three invertebrates and one fish, which is the most sensitive of the four. The saltwater Final Acute Value for selenium(IV) is 587.7 μg/L, which is slightly lower than the lowest Species Mean Acute Value.

Selenium(VI)

Among freshwater invertebrates, amphipods and cladocerans are quite sensitive to selenium(VI). Gammarus pseudolimnaeus, with a mean acute value of 65.38 μg/L, is the most sensitive tested freshwater species, and another

amphipod, Hyalella azteca, with an LC50 of 760 µg/L, is the third most sensitive species. The EC50 for Daphnia pulicaria is 246 µg/L (Boyum 1984) whereas the EC50s for Daphnia magna range from 570 to 5,300 µg/L from three independent studies.

The fathead minnow is the most sensitive freshwater fish species with which an acute test has been conducted on selenium(VI). Five 96-hr exposures resulted in LC50s ranging from 2,300 to 12,500 µg/L. One test (Spehar 1986) was a flow-through test in which the concentrations were measured. The tests conducted with the fathead minnow in the hardest water (323 mg/L as $CaCO_3$) gave 96-hr LC50s from 11,000 to 12,500 µg/L (Table 1) and a 48-day LC50 of 2,000 µg/L (Table 6). The hydroid, Hydra sp., was about as sensitive to selenium(VI) as the fathead minnow (Table 1). Other species were quite resistant with LC50s ranging from 20,000 µg/L for a midge, Paratanytarsus parthenogeneticus, to 442,000 µg/L for a leech, Nephelopsis obscura.

Of the eleven genera for which freshwater mean acute values are available for selenium(VI), the most sensitive, Gammarus, is 6,760 times more sensitive than the most resistant, Nephelopsis. The range of sensitivities of the four most sensitive genera is a factor of 84. The freshwater Final Acute Value for selenium(VI) was calculated to be 25.65 µg/L. This Final Acute Value is substantially below the acute value of the most sensitive freshwater species, because data are available for only eleven genera and because of the large differences between the values for the four most sensitive genera.

The only species with which acute tests have been conducted on selenium(VI) in salt water is the striped bass (Table 1). Klauda (1985) obtained 96-hr LC50s of 9,790 and 85,840 µg/L with prolarvae and juvenile striped bass, respectively.

Species Mean Acute Values have been determined for both selenium(IV) and selenium(VI) with ten freshwater species (Table 3) and one saltwater species (Table 1). For ten of these eleven species selenium(IV) is 1.6 to 6.3 times more toxic than selenium(VI). For the freshwater Gammarus pseudolimnaeus, however, selenium(VI) is 41 times more toxic. Acute tests were conducted on both selenium(IV) and selenium(VI) with this gammarid by the same investigators in 1985 and in 1987 (Brooke 1987; Brooke et al. 1985). This species is moderately sensitive to selenium(IV) but is very sensitive to selenium(VI). The Final Acute Value for selenium(VI) is fourteen times lower than that for selenium(IV) because fewer Genus Mean Acute Values are available for selenium(VI) and because of the low acute value obtained with Gammarus pseudolimnaeus.

Chronic Toxicity to Aquatic Animals

Selenium(IV)

The available data that are usable according to the Guidelines concerning the chronic toxicity of selenium(IV) and selenium(VI) are presented in Table 2. Chronic toxicity tests have been conducted on selenium(IV) with five freshwater species, four of which are acutely sensitive species (Table 3). The rainbow trout is both the most acutely resistant of these five species, and the most chronically sensitive, and thus has a much larger acute-chronic ratio than the other four species. Goettl and Davies (1977) exposed rainbow trout to selenium(IV) for 27 months, and they found that survival of fish exposed to 60 μg/L was similar to survival of control fish. Survival of fish exposed to 130 μg/L was about 50% of that of the controls and about 16% of these survivors were deformed, even though no control fish were deformed. Hodson et al. (1980) found that 47 to 53 μg/L caused a small

reduction in percent hatch of rainbow trout, but did not reduce survival of sac or swim-up fry. The small reduction in percent hatch is not considered unacceptable for the purposes of deriving water quality criteria. The data of Goettl and Davies (1977) indicated that the acute-chronic ratio was less than 187.2, and the data of Hodson et al. (1980) gave a ratio of 141.5.

In 90-day exposures starting with newly hatched fry, Hunn et al. (1987) found that selenium(IV) at concentrations of 12 µg/L and greater significantly reduced the concentration of calcium in bone of rainbow trout. However, the expected resulting decrease in the toughness and/or strength of the bone did not occur. A 90-day LC50 of 55.2 µg/L was calculated from the published data on percent survival, allowing for 8.9% spontaneous mortality (Table 6). The Guidelines (page 17) specify division of an LC50 by 2 to calculate a concentration that will not severely affect too many of the organisms. Division of 55.2 µg/L by 2 results in 27.6 µg/L.

The other four freshwater species with which chronic tests have been conducted on selenium(IV), including one fish species, are all acutely more sensitive, and chronically more resistant, than the rainbow trout. Kimball (Manuscript) conducted an early life-stage test on selenium(IV) with fathead minnows. A selenium(IV) concentration of 153 µg/L reduced survival by 32% and reduced weight by 18.5%. At a concentration of 83 µg/L, survival was reduced by 2% and weight was reduced by 9.6%. The resulting chronic value and acute-chronic ratio were 112.7 µg/L and 6.881, respectively.

Kimball (Manuscript) also studied the effects of selenium(IV) on survival and reproduction of Daphnia magna in a 28-day renewal test. Survival and reproduction of Daphnia magna exposed to 70 µg/L were similar to those of control animals. Survival at 120 µg/L was 100%, but reproduction, expressed as mean young per adult, was reduced 27% compared to the control

animals. The chronic value and acute-chronic ratio were 91.65 µg/L and 13.31, respectively. Adams and Heidolph (1985) also reported results of a life-cycle test with Daphnia magna on selenium(IV). The test was at a hardness of 240 to 310 mg/L and the chronic value was 161.5 µg/L. An acute-chronic ratio cannot be calculated from this chronic value, however, because it appears that the acute test reported by Adams and Heidolph (1985) was conducted in a different water.

Owsley (1984) and Owsley and McCauley (1986) reported the results of an exposure of four successive generations of the cladoceran, Ceriodaphnia affinis, to selenium(IV), but the concentrations in the test solutions were not adequately measured. A concentration of 200 µg/L severely affected all four generations, and the amount of effect increased with each successive generation. A concentration of 100 µg/L caused an unacceptable effect on only the second generation. The chronic value from this test would probably be close to 100 µg/L, and the acute-chronic ratio would be close to 6.

Reading (1979) and Reading and Buikema (1983) reported the chronic effects of selenium(IV) on the survival, growth, and reproduction of Daphnia pulex in a 28-day renewal test. At the end of the test, survival, total number of young per adult, and mean brood size at 600 µg/L were equal to or greater than those of the control daphnids, even though some differences were observed for some broods during the test. A concentration of 800 µg/L caused about a 40% reduction in the mean total number of live young per adult. The resulting chronic value was 692.8 µg/L and the acute-chronic ratio was 5.586.

Data on the chronic toxicity of selenium(IV) are available for two saltwater species, the mysid, Mysidopsis bahia, and the sheepshead minnow, Cyprinodon variegatus (Table 2). The life-cycle test with Mysidopsis bahia

was started with 48-hr post-release juveniles and lasted for 28 days (Ward et al. 1981). Exposure to concentrations of 320 μg/L or greater significantly reduced survival of the first-generation mysids. No offspring were produced by mysids that survived exposure to 580 μg/L, and the number of offspring produced per female was significantly lower in 320 μg/L than in the control treatment. All offspring produced in all treatments survived until the end of the test. At 140 μg/L, survival and reproduction were reduced 18% and 22%, respectively, compared to the controls, but these reductions were not statistically significant. The chronic value for Mysidopsis bahia is 211.7 μg/L and the acute-chronic ratio is 7.085.

An early life-stage test was performed with the sheepshead minnow (Ward et al. 1981). The test was started with newly-fertilized eggs and extended for two weeks after hatch to measure survival and growth of juveniles. Percent hatch was reduced 0 to 4% by concentrations of 970, 1,900, and 3,600 μg/L. Survival of juveniles was reduced 4% by 470 μg/L, 24% by 970 μg/L, and more than 90% at higher concentrations. Growth was reduced 8% by selenium concentrations of 470 and 970 μg/L. The resulting chronic value for Cyprinodon variegatus is 675.2 μg/L and the acute-chronic ratio is 10.96.

Acute-chronic ratios have been determined for selenium(IV) with three of the seven most acutely sensitive freshwater species. These ratios range from 5.586 to 13.31 (Table 3). The two acute-chronic ratios that were determined with saltwater species also fall within this range. The Final Acute-Chronic Ratio of 8.314 was calculated as the geometric mean of these five ratios. The high acute-chronic ratio obtained with the rainbow trout was not used in the calculation of the Final Acute-Chronic Ratio because this is an acutely resistant species. Division of the Final Acute Values by the Final

Acute-Chronic Ratio results in freshwater and saltwater Final Chronic Values of 44.72 and 70.69 μg/L, respectively. Based on the data reported by Hunn et al. (1987) for rainbow trout, the freshwater Final Chronic Value is lowered to 27.6 μg/L to protect this important species. The saltwater Final Chronic Value is quite a bit lower than the two saltwater chronic values, but neither of the saltwater species with which chronic tests have been conducted is acutely sensitive to selenium(IV).

Selenium(VI)

Chronic tests have been conducted on selenium(VI) with three freshwater species (Table 2). Some additional chronic tests have been conducted by exposing freshwater animals to selenium(VI) in food and water simultaneously. Dunbar et al. (1983) conducted a 32-day renewal life-cycle test with D. magna. Selenium(VI) at concentrations of 1,730 and 2,310 μg/L reduced the total young production by 3.3 and 25%, respectively. The chronic value was 1,999 and the acute-chronic ratio was 2.651.

Boyum (1984) conducted three life-cycle tests on selenium(VI) with daphnids but did not measure the concentrations of selenium in any of the tests. In all three tests, the nominal concentrations of selenium were 0, 50, 100, 500, and 1,000 μg/L. In one test with Daphnia magna and in one test with D. pulicaria, the animals were fed algae that had grown for 48 hours in the same concentration of selenium(VI) to which the daphnids themselves were exposed. In the third test, D. magna was fed algae that had been raised in control water. In this third test, the intrinsic growth rate was reduced 52% at the concentration of 50 μg/L. In the tests in which the algae contained selenium, the intrinsic growth rates of D. magna and D. pulicaria were reduced 8.6 and 13%, respectively, by 50 μg/L. When the daphnids were fed algae that contained selenium, D. pulicaria was affected more than D. magna at each

concentration of selenium. Also at each concentration of selenium, D. magna was affected less when it received selenium from both food and water than when it received selenium from only water. Separate tests showed that selenomethionine in water and selenium in algae independently reduced the uptake of selenium(VI) from water by D. magna.

Daphnia magna was much more sensitive to selenium(VI) in the tests reported by Boyum (1984) than in those reported by Dunbar et al. (1983). It is interesting that the dilution water used by Boyum contained 21.5 mg sulfate/L, whereas that used by Dunbar et al. contained about 174 mg sulfate/L.

Spehar (1986) reported results of a 90-day early life-stage test with rainbow trout. No fish survived at 6,300 µg/L or higher concentrations. A concentration of 3,800 µg/L reduced survival and weight by 93% and 24%, respectively. Survival and weight were reduced 7% and 12% by 2,200 µg/L. The chronic value was 2,891 µg/L and the acute-chronic ratio was 16.26.

Spehar (1986) also reported results of a 32-day early life-stage test with the fathead minnow. No fish survived at 2,900 µg/L, and 1,520 µg/L reduced both survival and weight by more than 60%. At 820 µg/L, survival was as good as in the control treatment, but weight was reduced by 34%. Weight was reduced only 3% by 390 µg/L. Thus this test resulted in a chronic value of 565.5 µg/L and an acute-chronic ratio of 9.726. Brooks et al. (1984) exposed fathead minnows throughout a life cycle to selenium(VI) in the range of 40 to 50 µg/L. The fish were fed a food that was specially prepared (see also Bertram and Brooks 1986) to simulate a food chain in water that contained the same concentration of selenium(VI). Although a malfunction of the diluter caused the concentration of selenium to be 2 to 5 times higher for up to one week, no adverse effects on survival, growth, or reproduction were observed.

The three available acute-chronic ratios for selenium(VI) show a consistent pattern in that the more acutely sensitive species have a lower ratio (Table 3). Because it is meant to apply to sensitive species, the Final Acute-Chronic Ratio was set equal to 2.651, the ratio obtained with the most acutely sensitive species with which a chronic test has been conducted. Division of the freshwater Final Acute Value for selenium(VI) by the Final Acute-Chronic Ratio results in a freshwater Final Chronic Value of 9.676 μg/L, which is substantially below the three available experimentally determined chronic values.

No data are available concerning the chronic toxicity of selenium(VI) to saltwater animals.

Chronic toxicity tests have been conducted on both selenium(IV) and selenium(VI) with three species (Table 2). With all three species, selenium(IV) was 5 to 32 times more toxic than selenium(VI), which is similar to the relative acute toxicities of these two oxidation states. Nine Species Mean Acute-Chronic Ratios are available for the two oxidation states (Table 3). The ratio determined for selenium(IV) with rainbow trout is 141.5, but the other eight ratios are all between 2.6 and 17.

Toxicity to Aquatic Plants

Selenium(IV)

Data are available on the toxicity of selenium(IV) to nine species of freshwater algae (Table 4). Results ranged from an LC50 of 30,000 μg/L for the blue-green alga, Anacystis nidulans (Kumar and Prakash 1971) to 522 μg/L for incipient inhibition of the green alga, Scenedesmus quadricauda (Bringmann and Kuhn 1977a,1978a,b,1979,1980b). Foe and Knight (Manuscript) found that 75 μg/L decreased the dry weight of Selenastrum

capricornutum (Table 6). Wehr and Brown (1985) reported that 320 µg/L increased the growth of the alga Chrysochromulina breviturrita. Thus the sensitivities of freshwater algae to selenium(IV) cover about the same range as the acute and chronic sensitivities of freshwater animals.

The 96-hr EC50 for the saltwater diatom, Skeletonema costatum, is 7,930 µg/L, based on reduction in chlorophyll a (Table 4). Growth of Chlorella sp., Platymonas subcordiformis, and Fucus spiralis increased at selenium(IV) concentrations from 10 to 10,000 µg/L (Table 6). These data suggest that saltwater plants will not be adversely affected by concentrations of selenium(IV) that do not affect saltwater animals.

Selenium(VI)

Growth of several species of green algae were affected by concentrations ranging from 10 to 300 µg/L (Table 4). Blue-green algae appear to be much more resistant to selenium(VI) with 10,000 µg/L being the lowest concentration reported to affect growth. Kumar (1964) found that a blue-green alga developed and lost resistance to selenium(VI). The difference in the sensitivities of green and blue-green algae to selenium(VI) might be of ecological significance, particularly in bodies of water susceptible to nuisance algal blooms. For example, Patrick et al. (1975) reported that a concentration of 1,000 µg/L caused a natural assemblage of algae to shift to a community dominated by blue-green algae.

At 10,000 µg/L, selenium(VI) is lethal to four species of saltwater phytoplankton and lower concentrations increase or decrease growth (Table 6). Concentrations as low as 10 µg/L reduced growth of Porphyridium cruentum (Wheeler et al. 1982).

Although selenium(IV) appears to be more acutely and chronically toxic than selenium(VI) to most aquatic animals, this does not seem to be true for

aquatic plants. Selenium(IV) and selenium(VI) are about equally toxic to the freshwater algae Anabaena cylindrica, Anabaena variabilis, Anacystis nidulans, and Scenedesmus dimorphus (Kumar and Prakash 1971; Moede et al. 1980). The two oxidation states equally stimulated growth of Chrysochromulina breviturrita (Wehr and Brown 1985.) On the other hand, selenium(VI) is more toxic than selenium (IV) to the freshwater Selenastrum capricornutum (Richter 1982) and the saltwater Chorella sp. and Platymonas subcordiformis (Wheeler et al. 1982). In addition, Fries (1982) found that growth of thalli of the brown macroalga, Fucus spiralis, was stimulated more by exposure to selenium(IV) at 2.605 µg/L than to the same concentration of selenium(VI).

A Final Plant Value, as defined in the Guidelines, cannot be obtained because no test in which the concentrations of selenium(IV) or selenium(VI) were measured and the endpoint was biologically important has been conducted with an important aquatic plant species.

Bioaccumulation

Selenium(IV)

Bioconcentration factors (BCFs) for selenium(IV) that have been obtained with freshwater species range from 2 for the muscle of rainbow trout to 452 for the bluegill (Table 5). Adams (1976) studied both uptake and elimination of selenium-75 by fathead minnows at average concentrations of 12, 24, and 50 µg/L. He found that concentrations in whole fish and in individual tissues increased at a rapid rate during the first eight days and at a slower rate for the next 88 days. Steady-state was approached, but not reached, in 96 days. The highest concentrations were found in viscera, possibly due to uptake of selenium adhering to food. Elimination of selenium was curvilinear and became asymptotic with the time axis after 96 days. Elimination was most

rapid from the viscera with a half-life of 5.1 days, but the half-life of selenium in other tissues was greater than 50 days.

Adams (1976) also conducted uptake studies with rainbow trout exposed for 48 days to selenium(IV) at concentrations ranging from 310 to 950 μg/L. Some of the trout died, and concentrations were somewhat higher in dead fish than in survivors. As with the fathead minnow, the viscera contained more selenium than gill or muscle. Based on his tests with the two species, Adams (1976) concluded that there was an inverse relationship between BCF and the concentration of selenium(IV) in water.

Hodson et al. (1980) exposed rainbow trout to selenium(IV) from fertilization until 44 weeks posthatch. At 53 μg/L in the water the BCF ranged from 8 for whole body to 240 for liver. They concluded that selenium in tissues did not increase in proportion to selenium(IV) in water.

Barrows et al. (1980) exposed bluegills to selenious acid for 28 days. They reported a maximum BCF in the whole fish of 20 and a half-life of between one and seven days. If bluegills bioconcentrate selenium in the same manner as the rainbow trout used by Adams (1976), the 28-day exposure might not have been long enough to reach steady-state.

Lemly (1982) exposed bluegills and largemouth bass to 10 μg/L for 120 days to determine the effect of hardness and temperature on uptake and elimination. For bluegills, the geometric mean whole-body BCF at 20° and 30°C was 452. For largemouth bass in similar tests, the BCF was 295. For both species, the spleen, liver, kidney, and heart had higher concentrations than the whole body. Neither water temperature nor hardness had a significant effect on concentrations in tissue after 90 days, although earlier values were influenced. After 30 days in clean water, selenium concentrations remained unchanged in spleen, liver, kidney, and white muscle, but the half-life for selenium in gills and erythrocytes was less than 15 days.

Steady-state BCFs with two saltwater species ranged from 2.88 in chela muscle of adult shore crab, Carcinus maenas (Bjerregaard 1982,1985) to 200 in whole adult euphausiids, Meganyctiphanes norvegica (Fowler and Benayoun 1976c). Selenium was accumulated to a higher concentration in gill than in hepatopancreas or muscle of the shore crab during exposure to 250 μg/L. The authors suggested that much of the selenium associated with the gill might be sorbed to the gill surface.

Ingestion of food organisms that had been exposed to selenium(IV) can be an important source of exposure of fish to selenium (Hodson and Hilton 1983; Sandholm et al. 1973; Turner and Swick 1983). Addition of selenium(IV) to food reduced survival of rainbow trout (Goettl and Davies 1978). Rudd and Turner(1983a,b) found that the bioaccumulation of selenium by fish was reduced by sediment and by increased primary productivity. Fowler and Benayoun (1976) reported that the BAF for selenium(IV) from food plus water was four times higher for an euphausiid than the BCF (uptake from water alone). The blue mussel, Mytilus edulis, accumulated selenium at a slow rate when exposed to selenium(IV), but did not accumulate selenium when exposed to bis(2-carboxybenzyl)selenium (Pelletier 1986a).

Selenium(VI)

Bertram and Brooks (1986) exposed adult fathead minnows to sodium selenate in water, in food, and in food and water together. The food was specially prepared by raising algae in a medium containing selenium(VI), feeding the algae to daphnids, mixing the exposed daphnids with unexposed daphnids, dewatering to form a "cake", and freezing. Uptake of selenium(VI) from only water reached steady-state within 28 days. The whole-body BCFs ranged from 1 to 52 and decreased as the concentration in water increased (Table 5). Uptake of selenium(VI) from food alone or from food and water together did not reach

steady-state in eight and eleven weeks, respectively. Uptake from food and water were additive.

When juvenile striped bass were exposed in salt water for 60 days to selenium(VI) at concentrations of 90 and 1,290 μg/L, the whole-body concentrations were within a factor of two of the concentrations in control fish (Klauda 1985).

Selenium(IV) was bioconcentrated more than selenium(VI) by saltwater phytoplankton communities (Wrench and Measures 1982), a freshwater duckweed (Bulter and Peterson 1967), and two saltwater invertebrates (Fowler and Benayoun 1976a).

No U.S. FDA action level or other maximum acceptable concentration in tissue, as defined in the Guidelines, is available for selenium and, therefore, no Final Residue Value can be calculated.

Other Data

Selenium(IV)

Additional data on the lethal and sublethal effects of selenium on aquatic species are presented in Table 6. Bringmann and Kuhn (1959a,b,1976, 1977a,1979,1980b,1981), Jakubczak et al. (1981), and Patrick et al. (1975) reported the concentrations of selenium(IV) that caused incipient inhibition (defined variously, such as the concentration resulting in a 3% reduction in growth) for algae, bacteria, and protozoans (Table 6). Although incipient inhibition might be statistically significant, its ecological importance is unknown. Jones and Stadtman (1977) reported stimulation of growth of an anaerobic bacterium exposed to 49 μg/L. Selenium(IV) at a concentration of 100 μg/L did not affect crustacean communities in enclosures in a lake contaminated by mercury (Salki et al. 1985).

Short and Wilber (1980) reported that the calcium balance in the crayfish, Orconectes immunis, was altered by a 30-day exposure to a selenium concentration of 10 µg/L. Hodson et al. (1980) found delayed mortality during a 4-day period following cessation of exposure to selenium(IV). Hilton et al. (1982) studied the uptake from food, distribution, and elimination of selenium(IV) by rainbow trout. Mancini (1983) calculated detoxification rates for selenium in various fishes.

Selenium(VI)

Dunbar et al. (1983) exposed fed D. magna to selenium(VI) for seven days and obtained an LC50 of 1,870 µg/L. This value is in the range of the 48-hr EC50s in Table 1.

Watenpaugh and Beitinger (1985a) found that fathead minnows did not avoid 11,200 µg/L during 30-minute exposures (Table 6). These authors also reported (1985b) a 24-hr LC50 of 82,000 µg/L for the same species and they found (1985c) that the thermal tolerance of the species was reduced by 22,200 µg/L. Bennett et al. (1986) raised rotifers on algae that had been exposed to selenium(VI). Fathead minnow larvae that were fed the contaminated rotifers weighed less than larvae that were fed control rotifers. Westerman and Birge (1978) exposed channel catfish embryos and newly hatched fry for 8.5 to 9 days to an unspecified concentration of selenium(VI). Albinism was observed in 12.1 to 36.9% of the fry during the five years of such exposures.

The respiratory rate of the eastern oyster, Crassostrea virginica, was unaffected by exposure to selenium(VI) at 400 µg/L for 14 days (Fowler et al. 1981). Embryos of the striped bass were quite resistant to selenium(VI) in dilute salt water (Klauda 1985). There was a 93% successful hatch of embryos at 200,000 µg/L, but 50% of 72-day-old juveniles died after four days at 87,000 µg/L. Exposure of juvenile fish for up to 65 days to

concentrations of selenium(VI) between 39 and 1,360 μg/L caused developmental anomalies and pathological lesions.

Field Studies

Studies on Belews Lake in North Carolina (e.g., Cumbie as quoted in Hodson et al. 1984; Cumbie and Van Horn 1978; Finley 1985; Lemly 1985a,b; Sorensen et al. 1984) and Hyco and Catfish Reservoirs in North Carolina (Baumann and Gillespie 1986; Gillespie and Baumann 1986; Sager and Cofield 1984) suggest that selenium might be more toxic to certain species of freshwater fish than has been observed in chronic toxicity tests. Other bodies of water in which the effects of selenium on aquatic organisms have been studied include a farm pond in New York (Furr et al. 1979; Gutenmann et al. 1976), various lakes and reservoirs in Colorado and Wyoming (Birkner 1978; Kaiser et al. 1979), a drainage system in South Carolina (Cherry and Guthrie 1978; Cherry et al. 1976,1979a,b,1984; Guthrie and Cherry 1976,1979), Martin Creek Reservoir in Texas (Garrett and Inman 1984; Sorensen and Bauer 1984a,b; Sorenson et al. 1982), and Kesterson Reservoir in California (Burton et al. 1987; Ohlendorf et al. 1986a,b; Saiki 1986a,b).

Such studies, however, have provided circumstantial, rather than definitive, data on the effects of selenium on aquatic life for two major reasons:

1. Few, if any, data are available concerning the oxidation state of selenium in the water. Because there are, as yet, no data to show that selenium(IV) and selenium(VI) are toxicologically or ecologically equivalent, it is difficult to interpret the results of field studies that do not use analytical methods (e.g., Oppenheimer et al. 1984; Robberecht and Van Grieken 1982; Uchida et al. 1980) that can separately

measure selenium(IV) and selenium(VI). On the other hand, it is likely that most ambient waters contain substantial concentrations of two or more oxidation states of selenium (see item 3 on page 2).

2. Unless the investigator controls the addition of the test material, rarely can a field study conclusively pinpoint the cause of any observed effects, because it is possible that the effects were caused by a combination of agents or by an unmeasured agent. However, if circumstantial evidence from a number of dissimilar situations points in the same direction, the inference becomes stronger.

In spite of the limitations of the available results of field studies, they do raise such important questions as:

a. What are the highest concentrations in water of selenium(-II), selenium(IV), selenium(VI), and their combinations that do not unacceptably reduce reproduction, and survival of the resulting young, of sensitive warmwater fishes?

b. What are the relative toxicities of selenium(-II), selenium(IV), selenium(VI), and their combinations in food and in water and are the two sources additive?

c. Are selenium(-II), selenium(IV), and selenium(VI) toxicologically or ecologically equivalent in aquatic ecosystems?

Such questions are important and can be answered with properly designed field and laboratory studies.

The severe effects that were observed on the fish community in Belews Lake have been attributed, with differing degrees of certainty by various authors, to the 10 μg selenium/L in the lake. Although selenium is certainly a good candidate for the cause of the observed effects, studies on Belews Lake cannot establish a cause-effect relationship because a variety of

other inorganic and organic materials undoubtedly entered the lake with the selenium. Studies on other bodies of water that contain selenium at concentrations in the range of 1 to 30 μg/L could help confirm or refute the theory that selenium is the primary cause of the effects observed in Belews Lake, especially if the selenium in the other bodies of water did not come from fly ash.

Several laboratory studies have attempted to confirm that selenium affected the fish community in Belews Lake. For example, Lemly (1982) exposed bluegills and largemouth bass to selenium(IV) at a concentration of 10 μg/L for 120 days. No mortality occurred in the test, whereas bluegills stocked into Belews Lake died in 3 to 4 months when kept in cages and died almost immediately when released into the lake (Cumbie as quoted in Hodson et al. 1984).

In a novel experiment, Gillespie and Baumann (1986) mated male and female bluegills from Hyco Reservoir, which contained a high concentration of selenium, with bluegills from Roxboro City Lake, which contained very little selenium. The young survived when females from Roxboro City Lake were mated with males from either source. When females from Hyco Reservoir were mated with males from either source, the young hatched but died before attaining the swim-up stage. The young that died also contained high concentrations of selenium, which they must have received from their mothers. It is, of course, possible that the young also received one or more toxicants in addition to selenium from their mothers because Hyco Reservoir is a cooling reservoir for a coal-fired electric power plant.

For 44 days Finley (1985) fed mayfly nymphs obtained from Belews Lake to four bluegills and fed cultured mealworms to four other bluegills. The nymphs contained 13.6 μg selenium/g (wet weight). The four fish fed mealworms

appeared healthy throughout the test, whereas three of the four fish fed the nymphs died. It is possible that bluegills were affected by Finley (1985) but not Lemly (1982) because the nymphs also contained one or more toxicants in addition to selenium, because the nymphs provided proportionately more selenium, or because the nymphs contained a more toxic form of selenium.

Several feeding studies have shown that aquatic species can be adversely affected by consuming food that contains 10 to 13 μg selenium/g. Thus these studies support the idea that the effects observed by Finley (1985) were caused by selenium. In two 42-week feeding studies, mortality of rainbow trout increased when their food contained selenium(IV) at a concentration of 9 μg/g (Goettl and Davies 1978). Hilton et al. (1980) reported that when rainbow trout were fed a food containing selenium(IV) at a concentration of 13 μg/g for twenty weeks, growth decreased and mortality increased. Hilton and Hodson (1983) obtained similar effects when trout consumed food containing 11 to 12 μg/g for sixteen weeks. In a fourth feeding study with rainbow trout, selenium(IV) at 11.4 μg/g (on a freeze-dried basis) reduced growth and increased mortality in a sixteen-week test (Hicks et al. 1984).

Although their tests on early life stages and smoltification of chinook salmon were possibly confounded by the presence of other pollutants, the results reported by Hamilton et al. (1986) support the results of other investigators that concentrations greater than 13 μg/g (reportedly as organoselenium) in food will unacceptably affect salmonids.

Heinz et al. (1987) fed adult mallards and their ducklings feed that contained selenium(IV) or selenomethionine. The number of 21-day old ducklings per hen was 9.7 for the controls and 2.0 for the animals that received food containing 10 μg selenium/g as selenomethionine. The treatments receiving 10 and 25 μg/g as selenium(IV) produced 8.1 and 0.2

ducklings per hen, respectively. Food containing 10 μg selenium/g as selenomethionine resulted in nearly ten times as much selenium in eggs as did food containing 10 μg/g as selenium(IV). Selenomethionine resulted in more selenium in egg white than yolk, but the opposite was true with selenium(IV).

These data indicate that rainbow trout, chinook salmon, and mallard ducks were affected when they consumed food that contained selenium in the range of 10 to 13 μg/g. Most of these studies were conducted by adding selenium(IV) to food, but it is likely that at least some of the selenium accumulated in food chain organisms would be in a more toxic form. These studies strongly indicate that the effects observed by Finley (1985) were indeed caused by selenium and that the 10 μg/L in Belews Lake caused the effects observed there. The concentration of selenium in an unaffected upper arm of Belews Lake was near or below the detection limit of 5 μg/L (North Carolina Department of Natural Resources and Community Development 1986).

The freshwater Criterion Continuous Concentration (CCC) should be between 10 μg/L and the concentration in the unaffected portion of Belews Lake, which is near or below 5 μg/L. Therefore, the CCC will be set at 5.0 μg/L. Eight of the nine Acute-Chronic Ratios in Table 3 are between 2.651 and 16.26, with a geometric means of 7.993. If the Final Acute-Chronic Ratio is assumed to be 7.993, the Final Acute Value would be 39.96 μg/L, and the Criterion Maximum Concentration would be 19.98 μg/L.

Unused Data

Some data on the effects of selenium on aquatic organisms were not used because the studies were conducted with species that are not resident in North America (e.g., Asanullah and Brand 1985; Asanullah and Palmer 1980; Fowler and Benayoun 1976a,b; Gotsis 1982; Hiraoka et al. 1985; Juhnke and Ludemann 1978;

Niimi and LaHam 1975,1976; Ringdal and Julshamn 1985; Shultz and Ito 1979; Srivastava and Tyagi 1983/1984; Wrench 1978). Results (e.g., Okasako and Siegel 1980) of tests conducted with brine shrimp, Artemia sp., were not used because these species are from a unique saltwater environment. Adams and Johnson (1981), Biddinger and Gloss (1984), Brooks (1984), Chapman et al. (1968), Davies (1978), Eisler (1985), Hall and Burton (1982), Hodson and Hilton (1983), Hodson et al. (1984), Jenkins (1980), Kay (1984), LeBlanc (1984), McKee and Wolf (1963), National Research Council (1976), North Carolina Department of Natural Resources and Community Development (1986), Phillips and Russo (1978), Thompson et al. (1972), and Versar (1975) compiled data from other sources.

Greenberg and Kopec (1986) and Hutchinson and Stokes (1975) did not specify the oxidation state of the selenium used in their tests. Data were not used when selenium was a component of an effluent, fly ash, formulation, mixture, sediment, or sludge (e.g., Burton et al. 1983; Fava et al. 1985; Hall et al. 1984; Hamilton et al. 1986; Hildebrand et al. 1976; Jay and Muncy 1979; MacFarlane et al. 1986; Phillips and Gregory 1980; Ryther et al. 1979; Seelye et al. 1982; Specht et al. 1984; Thomas et al. 1980b; Wong et al. 1982) unless data were available to show that the toxicity was the same as for selenium alone.

Braddon (1982), Christensen and Tucker (1976), Freeman and Sangalang (1977), and Olson and Christensen (1980) exposed enzymes, excised tissue, or tissue extracts. Results were not used when the test procedures, test material, or results were not adequately described (e.g., Bovee 1978; Gissel-Nielsen and Gissel-Nielsen 1973,1978; Greenberg and Kopec 1986; Nassos et al. 1980). Kaiser (1980) calculated the toxicities of selenium(IV) and selenium(VI) to Daphnia magna based on physiochemical parameters. Kumar

(1964) did not include a control treatment in the toxicity tests. The daphnids were probably stressed by crowding in the tests reported by Schultz et al. (1980). Siebers and Ehlers (1979) exposed too few test organisms, as did Owsley (1984) in some tests. Data were not used when the organisms were exposed to selenium by gavage or injection (Hilton et al. 1982; Kleinow 1984; Kleinow and Brooks 1986a,b; Sheline and Schmidt-Nielson 1977).

BCFs and BAFs from laboratory tests were not used when the tests were static or when the concentration of selenium in the test solution was not adequately measured or varied too much, (e.g., Nassos et al. 1980; Sharma and Davis 1980). Reports of the concentrations of selenium in wild aquatic organisms (e.g., Baumann and Gillespie 1986; Baumann and May 1984; Brezina and Arnold 1977; Birkner 1978; Cappon 1984; Cappon and Smith 1981,1982a,b; Cumbie and Van Horn 1978; Davoren 1986; Fowler et al. 1975; Froslie et al. 1985; Gillespie and Baumann 1986; Greig and Jones 1976; Heit and Klusek 1985; Heit et al. 1980; Johnson 1987; Kaiser et al. 1979; Lemly 1985a; Lowe et al. 1985; Lucas et al. 1970; Lytle and Lytle 1982; May and McKinney 1981; Mehrle et al. 1982; Moharram et al. 1987; Ohlendorf et al. 1986a,b,c; Okazaki and Panietz 1981; Pakkala et al. 1972; Payer and Runkel 1978; Payer et al. 1976; Pennington et al. 1982; Sager and Cofield 1984; Saiki 1986a,b; Shultz and Ito 1979; Seelye et al. 1982; Sorensen and Bauer 1984a,b; Sorensen et al. 1982,1983,1984; Speyer 1980; Uthe and Bligh 1971; Walsh et al. 1977; Weber 1985; Winger and Andreasen 1985; Winger et al. 1984; Woock and Summers 1984; Zatta et al. 1985) were not used to calculate BAFs when either the number of measurements of the concentration in water was too small or the range of the measured concentrations was too large.

Summary

Selenium(IV)

Acute values for 23 freshwater fish and invertebrate species in 22 genera range from 340 μg/L for the amphipod, Hyalella azteca, to 203,000 μg/L for the leech, Nephelopsis obscura. Although twelve of the twenty-three species are fishes, both the two most sensitive and the two most resistant species are invertebrates. Chronic values are available for two fishes and two invertebrates and range from >47 to 692 μg/L. In a separate test, a 90-day LC50 of 54 μg/L was obtained with rainbow trout. The acute-chronic ratios for the acutely more sensitive species range from 5.6 to 13.3.

Toxicity values for nine species of freshwater algae range from 500 to 30,000 μg/L. Uptake of selenium(IV) by fish takes about 100 days to reach steady-state and bioconcentration factors from 2 to 452 have been reported.

Acute toxicity values are available for 16 species of saltwater animals, including 8 invertebrates and 8 fishes, and range from 599 μg/L for larvae of the haddock, Melanogrammus aeglefinus, to 17,350 μg/L for adults of the fourspine stickleback, Apeltes quadracus. Fish and invertebrates have similar ranges of sensitivities, and the acute values for the seven most sensitive species differ only by a factor of 3.2. There was no consistent relationship between life stage of invertebrates or fish and their insensitivity to selenium(IV).

Chronic toxicity data are available for two saltwater animals, the mysid, Mysidopsis bahia, and the sheepshead minnow, Cyprinodon variegatus. The chronic values and the acute-chronic ratios are 211.7 μg/L and 7.085 for the mysid, and 675.2 μg/L and 10.96 for the sheepshead minnow. At a concentration of 7,930 μg/L, selenium(IV) caused a 50% reduction in chlorophyll a in a test with the saltwater diatom, Skeletonema costatum, but

growth of three species of algae was stimulated by concentrations of 10 to 10,000 µg/L. The steady-state bioconcentration factors for two saltwater species range from 3.88 in chela muscle of adult shore crabs, Carcinus maenas, to 200 in whole adult euphausiids, Meganyctiphanes norvegica.

Selenium(VI)

The acute toxicity of selenium(VI) has been determined with twelve freshwater animal species. The acute values range from 75 µg/L with the amphipod, Gammarus pseudolimnaeus, to 442,000 µg/L with the leech, Nephelopsis obscura. Chronic toxicity tests have been conducted with Daphnia magna, the fathead minnow, and the rainbow trout. The chronic values range from 565.5 to 1,999 µg/L, and the acute-chronic ratios range from 2.651 to 16.26. Selenium(VI) affected nine algal species at concentrations ranging from 10 to 39,000 µg/L. Bioaccumulation factors obtained with the fathead minnow ranged from 21 to 52 µg/L.

Few data are available concerning the effects of selenium(VI) on saltwater species. Acute toxicity tests with prolarvae and juveniles of striped bass, Morone saxatilis, resulted in 96-hr LC50s of 9,790 and 85,840 µg/L, respectively. No chronic tests have been conducted on selenium(VI) with saltwater animals. The growth of an alga was increased by 10 µg/L. Steady-state bioconcentration factors of 1 to 16 were obtained with juvenile striped bass.

Other

For ten of the eleven freshwater and saltwater fish and invertebrate species for which comparable acute data are available, selenium(IV) is 1.6 to 3.6 times more toxic than selenium(VI). For the eleventh species, selenium(IV) is 57 times less toxic. Chronic toxicity tests have been conducted on both selenium(IV) and selenium(VI) with three freshwater species

and no saltwater species. For all three animals selenium(IV) was 5 to 32 times more toxic than selenium(VI). Eight of the nine acute-chronic ratios available for the two oxidation states are between 2.6 and 17; the ninth ratio is 141.5 and was obtained with an acutely resistant species. In contrast to the data obtained with aquatic animals, selenium(VI) is either as toxic as or more toxic than selenium(IV) to aquatic plants. Selenium(IV) seems to be bioconcentrated more than selenium(VI) by aquatic plants and animals.

Salmonids and mallard ducks were severely affected when they consumed food that contained selenium at concentrations of 10 to 13 μg/g. It is likely that the populations of several species of warmwater fishes were destroyed by selenium at a concentration of 10 μg/L in Belews Lake.

National Criteria

The procedures described in the "Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses" indicate that, except possibly where a locally important species is very sensitive, freshwater aquatic organisms and their uses should not be affected unacceptably if the four-day average concentration of selenium does not exceed 5.0 μg/L more than once every three years on the average and if the one-hour average concentration does not exceed 20 μg/L more than once every three years on the average.

The procedures described in the "Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses" indicate that, except possibly where a locally important species is very sensitive, saltwater aquatic organisms and their uses should not be affected unacceptably if the four-day average concentration of selenium does not exceed 71 μg/L more than once every three years on the average and if

the one-hour average concentration does not exceed 300 μg/L more than once every three years on the average. If selenium is as toxic to saltwater fishes in the field as it is to freshwater fishes in the field, the status of the fish community should be monitored whenever the concentration of selenium exceeds 5.0 μg/L in salt water.

Implementation

Because of the variety of forms of selenium in ambient water and the lack of definitive information about their relative toxicities to aquatic species, no available analytical measurement is known to be ideal for expressing aquatic life criteria for selenium. Previous aquatic life criteria for metals and metalloids (U.S. EPA 1980b) were expressed in terms of the total recoverable measurement (U.S. EPA 1983a), but newer criteria for metals and metalloids have been expressed in terms of the acid-soluble measurement (1985b). Acid-soluble selenium (operationally defined as the selenium that passes through a 0.45 μm membrane filter after the sample has been acidified to a pH between 1.5 and 2.0 with nitric acid) is probably the best measurement at the present for the following reasons:

1. This measurement is compatible with nearly all available data concerning toxicity of selenium to, and bioaccumulation of selenium by, aquatic organisms. It is expected that the results of tests used in the derivation of the criteria would not have changed substantially if they had been reported in terms of acid-soluble selenium.
2. On samples of ambient water, measurement of acid-soluble selenium will probably measure all forms of selenium that are toxic to aquatic life or can be readily converted to toxic forms under natural conditions. In addition, this measurement probably will not measure several forms, such

as selenium that is occluded in minerals, clays, and sand or is strongly sorbed to particulate matter, that are not toxic and are not likely to become toxic under natural conditions.

3. Although water quality criteria apply to ambient water, the measurement used to express criteria is likely to be used to measure selenium in aqueous effluents. Measurement of acid-soluble selenium is expected to be applicable to effluents. If desired, dilution of effluent with receiving water before measurement of acid-soluble selenium might be used to determine whether the receiving water can decrease the concentration of acid-soluble selenium because of sorption.
4. The acid-soluble measurement is expected to be useful for most metals and metalloids, thus minimizing the number of samples and procedures that are necessary.
5. The acid-soluble measurement does not require filtration of the sample at the time of collection, as does the dissolved measurement.
6. For the measurement of total acid-soluble selenium the only treatment required at the time of collection is preservation by acidification to a pH between 1.5 and 2.0, similar to that required for the total recoverable measurement.
7. Durations of 10 minutes to 24 hours between acidification and filtration of most samples of ambient water probably will not substantially affect the result of the measurement of total acid-soluble selenium. However, acidification might not prevent oxidation or reduction of selenium(-II), selenium(VI), or selenium(IV) (May and Kane 1984). Therefore, measurement of acid-soluble selenium(IV) and/or acid-soluble selenium(VI) might require separation or measurement at the time of collection of the sample or special preservation to prevent conversion of one oxidation state of selenium to the other.

8. Ambient waters have much higher buffer intensities at a pH between 1.5 and 2.0 than they do at a pH between 4 and 9 (Stumm and Morgan 1981)
9. Differences in pH within the range of 1.5 to 2.0 probably will not affect the result substantially.
10. The acid-soluble measurement does not require a digestion step, as does the total recoverable measurement.
11. After acidification and filtration of the sample to isolate the acid-soluble selenium, the analysis for total acid-soluble selenium can be performed using either furnace or hydride atomic absorption spectrophotometric or ICP-atomic emission spectrometric analysis (U.S. EPA 1983a), as with the total recoverable measurement. It might be possible to separately measure acid-soluble selenium(IV) and acid-soluble selenium(VI) using the methods described by Oppenheimer et al. (1984), Robberecht and Van Grieken (1982), and Uchida et al. (1980).

Thus, expressing aquatic life criteria for selenium in terms of the acid-soluble measurement has both toxicological and practical advantages. The U.S. EPA is considering development and approval of a method for a measurement such as acid-soluble.

Metals and metalloids might be measured using the total recoverable method (U.S. EPA 1983a). This would have two major impacts because this method includes a digestion procedure. First, certain species of some metals and metalloids cannot be measured because the total recoverable method cannot distinguish between individual oxidation states. Second, in some cases these criteria would be overly protective when based on the total recoverable method because the digestion procedure will dissolve selenium that is not toxic and cannot be converted to a toxic form under natural conditions. Because no measurement is known to be ideal for expressing aquatic life criteria for

selenium or for measuring selenium in ambient water or aqueous effluents, measurement of both acid-soluble selenium and total recoverable selenium in ambient water or effluent or both might be useful. For example, there might be cause for concern when total recoverable selenium is much above an applicable limit, even though acid-soluble selenium is below the limit.

In addition, metals and metalloids might be measured using the dissolved method, but this would also have several impacts. First, whatever analytical method is specified for measuring selenium in ambient surface water will probably also be used to monitor effluents. If effluents are monitored by measuring only the dissolved metals and metalloids, the effluents might contain some selenium that would not be measured but might dissolve, due to dilution or change in pH or both, when the effluent is mixed with receiving water. Second, measurement of dissolved selenium requires filtration of the sample at the time of collection. Third, the dissolved measurement is especially inappropriate for use with such metals as aluminum that can exist as hydroxide and carbonate precipitates in toxicity tests and in effluents. Use of different methods for different metals and metalloids would be unnecessarily complicated. For these reasons, it is recommended that aquatic life criteria for selenium not be expressed as dissolved selenium.

As discussed in the Water Quality Standards Regulation (U.S. EPA 1983b) and the Foreword to this document, a water quality criterion for aquatic life has regulatory impact only after it has been adopted in a State water quality standard. Such a standard specifies a criterion for a pollutant that is consistent with a particular designated use. With the concurrence of the U.S. EPA, States designate one or more uses for each body of water or segment thereof and adopt criteria that are consistent with the use(s) (U.S.EPA

1983c,1987). In each standard a State may adopt the national criterion, if one exists, or, if adequately justified, a site-specific criterion.

Site-specific criteria may include not only site-specific criterion concentrations (U.S. EPA 1983c), but also site-specific, and possibly pollutant-specific, durations of averaging periods and frequencies of allowed excursions (U.S. EPA 1985c). The averaging periods of "one hour" and "four days" were selected by the U.S. EPA on the basis of data concerning how rapidly some aquatic species react to increases in the concentrations of some pollutants, and "three years" is the Agency's best scientific judgment of the average amount of time aquatic ecosystems should be provided between excursions (Stephan et al. 1985; U.S. EPA 1985c). However, various species and ecosystems react and recover at greatly differing rates. Therefore, if adequate justification is provided, site-specific and/or pollutant-specific concentrations, durations, and frequencies may be higher or lower than those given in national water quality criteria for aquatic life.

Use of criteria, which have been adopted in State water quality standards, for developing water quality-based permit limits and for designing waste treatment facilities requires selection of an appropriate wasteload allocation model. Although dynamic models are preferred for the application of these criteria (U.S. EPA 1985c), limited data or other considerations might require the use of a steady-state model (U.S. EPA 1986). Guidance on mixing zones and the design of monitoring programs is also available (U.S. EPA 1985c, 1987).

Table 1. Acute Toxicity of Selenium to Aquatic Animals

Species	Method[a]	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)[b]	Species Mean Acute Value (µg/L)	Reference
			FRESHWATER SPECIES			
			Selenium(IV)			
Hydra (adult), *Hydra* sp.	S, M	Sodium selenite	-	1,700	1,700	Brooke et al. 1985
Leech (adult), *Nephelopsis obscura*	S, M	Sodium selenite	49.8	203,000	203,000	Brooke et al. 1985
Snail (adult), *Aplexa hypnorum*	S, M	Sodium selenite	50.6	53,000	-	Brooke et al. 1985
Snail (adult), *Aplexa hypnorum*	S, M	Sodium selenite	49.8	23,000	34,910	Brooke et al. 1985
Snail, *Physa* sp.	S, U	Sodium selenite	45.7	24,100	24,100	Reading 1979
Cladoceran (<24 hr), *Ceriodaphnia affinis*	S, U	Sodium selenite	100.8	600	-	Owsley 1984; Owsley and McCauley 1986
Cladoceran (36-60 hr), *Ceriodaphnia affinis*	S, U	Sodium selenite	100.8	720	-	Owsley 1984
Cladoceran (84-108 hr), *Ceriodaphnia affinis*	S, U	Sodium selenite	100.8	640	-	Owsley 1984
Cladoceran (72-120 hr), *Ceriodaphnia affinis*	S, U	Sodium selenite	100.8	<480	<603.6	Owsley 1984

Table 1. (continued)

Species	Method[a]	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)[b]	Species Mean Acute Value (µg/L)	Reference
Cladoceran, *Daphnia magna*	S, U	Sodium selenite	214	2,500	-	Bringmann and Kuhn 1959a
Cladoceran, *Daphnia magna*	S, U	Selenious acid[c]	72	430	-	LeBlanc 1980
Cladoceran, *Daphnia magna*	S, M	Sodium selenite	129.5	1,100	-	Dunbar et al. 1983
Cladoceran, *Daphnia magna*	S, M	Sodium selenite	138	450	-	Boyum 1984
Cladoceran (<24 hr), *Daphnia magna*	S, U	Sodium selenite	-	215	-	Adams and Heidolph 1985
Cladoceran (<24 hr), *Daphnia magna*	S, U	Sodium selenite	40	870	-	Mayer and Ellersieck 1986
Cladoceran (<24 hr), *Daphnia magna*	S, U	Sodium selenite	280	2,370	-	Mayer and Ellersieck 1986
Cladoceran, *Daphnia magna*	S, M	Selenious acid	220[d]	1,220	855.8	Kimball, Manuscript
Cladoceran, *Daphnia pulex*	S, M	Sodium selenite	46.4	3,870	3,870	Reading 1979; Reading and Buikema 1983

Table 1. (continued)

Species	Method[a]	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)[b]	Species Mean Acute Value (µg/L)	Reference
Amphipod (adult), *Gammarus pseudolimnaeus*	S, M	Sodium selenite	48.3	4,300	-	Brooke et al. 1985
Amphipod (adult), *Gammarus pseudolimnaeus*	S, M	Sodium selenite	53.6	1,700	2,704	Brooke 1987
Amphipod, *Hyalella azteca*	F, M	Sodium selenite	329	340	340	Halter et al. 1980
Midge, *Chironomus plumosus*	S, U	Sodium selenite	39	24,150	-	Mayer and Ellersieck 1986
Midge, *Chironomus plumosus*	S, U	Sodium selenite	280	27,850	25,930	Mayer and Ellersieck 1986
Midge, *Tanytarsus dissimilis*	F, M	Selenium dioxide	48.0	42,500	42,500	Call et al. 1983
Rainbow trout, *Salmo gairdneri*	S, U	Sodium selenite	330	4,500	-	Adams 1976
Rainbow trout, *Salmo gairdneri*	S, U	Sodium selenite	330	4,200	-	Adams 1976
Rainbow trout, *Salmo gairdneri*	S, U	Sodium selenite	272	1,800	-	Hunn et al. 1987
Rainbow trout, *Salmo gairdneri*	F, M	Sodium selenite	30	12,500	-	Goettl and Davies 1976
Rainbow trout, *Salmo gairdneri*	F, M	Sodium selenite	135	8,800	10,490	Hodson et al. 1980

Table 1. (continued)

Species	Method[a]	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)[b]	Species Mean Acute Value (µg/L)	Reference
Brook trout (adult), *Salvelinus fontinalis*	F, M	Selenium dioxide	157	10,200	10,200	Cardwell et al. 1976a,b
Goldfish, *Carassius auratus*	F, M	Selenium dioxide	157	26,100	26,100	Cardwell et al. 1976a,b
Common carp, *Cyprinus carpio*	R, U	-	-	35,000	35,000	Sato et al. 1980
Fathead minnow, *Pimephales promelas*	S, U	Sodium selenite	312 (13°C)	10,500	-	Adams 1976
Fathead minnow, *Pimephales promelas*	S, U	Sodium selenite	312 (13°C)	11,300	-	Adams 1976
Fathead minnow, *Pimephales promelas*	S, U	Sodium selenite	303 (20°C)	6,000	-	Adams 1976
Fathead minnow, *Pimephales promelas*	S, U	Sodium selenite	303 (20°C)	7,400	-	Adams 1976
Fathead minnow, *Pimephales promelas*	S, U	Sodium selenite	292 (25°C)	3,400	-	Adams 1976
Fathead minnow, *Pimephales promelas*	S, U	Sodium Selenite	292 (25°C)	2,200	-	Adams 1976
Fathead minnow (30 days), *Pimephales promelas*	S, M	Sodium selenite	51.1	1,700	-	Brooke et al. 1985

Table 1. (continued)

Species	Method[a]	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)[b]	Species Mean Acute Value (µg/L)	Reference
Fathead minnow (juvenile), *Pimephales promelas*	S, U	Sodium selenite	40	7,760	-	Mayer and Ellersieck 1986
Fathead minnow (fry), *Pimephales promelas*	F, M	Selenium dioxide	157	2,100	-	Cardwell et al. 1976a,b
Fathead minnow (juvenile), *Pimephales promelas*	F, M	Selenium dioxide	157	5,200	-	Cardwell et al. 1976a,b
Fathead minnow, *Pimephales promelas*	F, M,	Selenious acid	220[d]	620	-	Kimball, Manuscript
Fathead minnow, *Pimephales promelas*	F, M	Selenious acid	220[d]	970	1,601	Kimball, Manuscript
White sucker, *Catostomus commersoni*	F, M	Sodium selenite	10.2	29,000	-	Klaverkamp et al. 1983a
White sucker, *Catostomus commersoni*	F, M	Sodium selenite	18	31,400	30,180	Duncan and Klaverkamp 1983
Striped bass (63 days), *Morone saxatilis*	S, U	Sodium selenite	40	1,325	-	Palawski et al. 1985
Striped bass (63 days), *Morone saxatilis*	S, U	Sodium selenite	285	2,400	1,783	Palawski et al. 1985
Channel catfish (juvenile), *Ictalurus punctatus*	S, M	Sodium selenite	49.8	16,000	-	Brooke et al. 1985

Table 1. (continued)

Species	Method[a]	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)[b]	Species Mean Acute Value (µg/L)	Reference
Channel catfish (juvenile), *Ictalurus punctatus*	S, U	Sodium selenite	41	4,110	-	Mayer and Ellersieck 1986
Channel catfish, *Ictalurus punctatus*	F, M	Selenium dioxide	157	13,600	13,600	Cardwell et al. 1976a,b
Flagfish, *Jordanella floridae*	F, M	Selenium dioxide	157	6,500	6,500	Cardwell et al. 1976a,b
Mosquitofish, *Gambusia affinis*	S, U	Sodium selenite	45.7	12,600	12,600	Reading 1979
Bluegill (juvenile), *Lepomis macrochirus*	S, M	Sodium selenite	50.5	12,000	-	Brooke et al. 1985
Bluegill, *Lepomis macrochirus*	F, M	Selenium dioxide	157	28,500	28,500	Cardwell et al. 1976a,b
Yellow perch, *Perca flavescens*	F, M	Sodium selenite	10.2	11,700[e]	11,700	Klaverkamp et al. 1983a
			Selenium(VI)			
Hydra (adult), *Hydra* sp.	S, M	Sodium selenate	53.6	7,300	7,300	Brooke et al. 1985
Leech (adult), *Nephelopsis obscura*	S, M	Sodium selenate	49.3	442,000	442,000	Brooke et al. 1985

Table 1. (continued)

Species	Method[a]	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)[b]	Species Mean Acute Value (µg/L)	Reference
Snail, *Aplexa hypnorum*	S, M	Sodium selenate	51.0	193,000	193,000	Brooke et al. 1985
Cladoceran, *Daphnia magna*	S, M	Sodium selenate	129.5	5,300	-	Dunbar et al. 1983
Cladoceran, *Daphnia magna*	S, M	Sodium selenate	138	1,010	-	Boyum 1984
Cladoceran, *Daphnia magna*	S, M	Sodium selenate	48.1	570	1,450	Brooke et al. 1985
Cladoceran, *Daphnia pulicaria*	S, M	Sodium selenate	138	246	246	Boyum 1984
Amphipod (adult), *Gammarus pseudolimnaeus*	S, M	Sodium selenate	46.1	75	-	Brooke et al. 1985
Amphipod (adult), *Gammarus pseudolimnaeus*	S, M	Sodium selenate	51.0	57	65.38	Brooke 1987
Amphipod, *Hyalella azteca*	F, U	Sodium selenate	336.8	760	760	Adams 1976
Midge (3rd instar), *Paratanytarsus parthenogeneticus*	S, M	Sodium selenate	49.4	20,000	20,000	Brooke et al. 1985
Rainbow trout (juvenile), *Salmo gairdneri*	S, M	Sodium selenate	51.0	24,000	-	Brooke et al. 1985
Rainbow trout, *Salmo gairdneri*	F, M	Sodium selenate	45	47,000	47,000	Spehar 1986

Table 1. (continued)

Species	Method[a]	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 ($\mu g/L$)[b]	Species Mean Acute Value ($\mu g/L$)	Reference
Fathead minnow, *Pimephales promeles*	S, U	Sodium selenate	323	11,800	-	Adams 1976
Fathead minnow, *Pimephales promeles*	S, U	Sodium selenate	323	11,000	-	Adams 1976
Fathead minnow, *Pimephales promeles*	S, U	Sodium selenate	323	12,500	-	Adams 1976
Fathead minnow (juvenile), *Pimephales promelas*	S, M	Sodium selenate	47.9	2,300	-	Brooke et al. 1985
Fathead minnow, *Pimephales promelas*	F, M	Sodium selenate	46	5,500	5,500	Spehar 1986
Channel catfish (juvenile), *Ictalurus punctatus*	S, M	Sodium selenate	51.0	66,000	66,000	Brooke et al. 1985
Bluegill (juvenile), *Lepomis macrochirus*	S, M	Sodium selenate	50.4	63,000	63,000	Brooke et al. 1985

Table 1. (continued)

Species	Method[a]	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)[b]	Species Mean Acute Value (µg/L)	Reference
			SALTWATER SPECIES			
			Selenium(IV)			
Blue mussel (embryo), *Mytilus edulis*	S, U	Selenium oxide	33.79	>10,000	>10,000	Martin et al. 1981
Pacific oyster (embryo), *Crassostrea gigas*	S, U	Selenium oxide	33.79	>10,000	-	Glickstein 1978; Martin et al. 1981
Pacific oyster (embryo) *Crassostrea gigas*	S, U	Sodium selenite	33.79	>10,000	>10,000	Glickstein 1978
Copepod (adult), *Acartia clausi*	S, U	Selenious acid	30	2,110	2,110	Lussier 1986
Copepod (adult), *Acartia tonsa*	S, U	Selenious acid	30	839	839	Lussier 1986
Mysid (juvenile), *Mysidopsis bahia*	S, U	Selenious acid	-	600	-	U.S. EPA 1978
Mysid (juvenile), *Mysidopsis bahia*	F, M	Selenious acid	15-20	1,500	1,500	Ward et al. 1981
Brown shrimp (juvenile), *Penaeus aztecus*	S, U	Sodium selenite	30	1,200	1,200	Ward et al. 1981
Dungeness crab (zoea I), *Cancer magister*	S, U	Selenium oxide	33.79	1,040	1,040	Glickstein 1978

Table 1. (continued)

Species	Method[a]	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)[b]	Species Mean Acute Value (µg/L)	Reference
Blue crab (juvenile), *Callinectes sapidus*	S, U	Sodium selenite	30	4,600	4,600	Ward et al. 1981
Haddock (larva), *Melanogrammus aeglefinus*	S, U	Selenious acid	30	599	599	Cardin 1986
Sheepshead minnow (juvenile), *Cyrinodon variegatus*	S, U	Selenious acid	-	6,700	-	Heitmuller et al. 1981
Sheepshead minnow (juvenile), *Cyrinodon variegatus*	F, M	Sodium selenite	30	7,400	7,400	Ward et al. 1981
Atlantic silverside (juvenile), *Menidia menidia*	S, U	Selenious acid	30	9,725	9,725	Cardin 1986
Fourspine stickleback (adult), *Apeltes quadracus*	S, U	Selenious acid	30	17,350	17,350	Cardin 1986
Striped bass, *Morone saxatilis*	S, U	Sodium selenite	1	1,550	1,550	Palawski et al. 1985
Pinfish (juvenile), *Lagodon rhomboides*	S, U	Sodium selenite	30	4,400	4,400	Ward et al. 1981
Summer flounder (embryo), *Paralichthys dentatus*	S, U	Selenious acid	30.2	3,497	3,497	Cardin 1986

Table 1. (continued)

Species	Method[a]	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)[b]	Species Mean Acute Value (µg/L)	Reference
Winter flounder (larva), Pseudopleuronectes americanus	S, U	Selenious acid	30	14,240	-	Cardin 1986
Winter flounder (larva), Pseudopleuronectes americanus	S, U	Selenious acid	28	15,070	14,650	Cardin 1986
			Selenium(VI)			
Striped bass (prolarvae), Morone saxatilis	F,M	Sodium selenate	3.5-4.2	9,790	-	Klauda 1985
Striped bass (juvenile), Morone saxatilis	F,M	Sodium selenate	6.0-6.5	85,840[f]	9,790	Klauda 1985

[a] S = Static; R = Renewal; F = Flow-through; M = Measured, U = Unmeasured.

[b] Concentration of selenium, not the chemical.

[c] Reported by Barrows et al. (1980) in work performed in the same laboratory under the same contract.

[d] From Smith et al. (1976).

[e] Calculated from regression equation.

[f] Not used in calculation of Species Mean Acute Value because data are available for a more sensitive life stage.

Table 2. Chronic Toxicity of Selenium to Aquatic Animals

Species	Test[a]	Chemical	Hardness (mg/L as $CaCO_3$)	Chronic limits (µg/L)[b]	Chronic Value (µg/L)	Reference
FRESHWATER SPECIES						
Selenium(IV)						
Cladoceran, *Daphnia magna*	LC	Sodium selenite	240-310	110-237	161.5	Adams and Heidolph 1985
Cladoceran, *Daphnia magna*	LC	Selenious acid	220[c]	70-120	91.65	Kimball, Manuscript
Cladoceran, *Daphnia pulex*	LC	Sodium selenite	46.4	600-800	692.8	Reading 1979; Reading and Buikema 1983
Rainbow trout, *Salmo gairdneri*	ELS	Sodium selenite	30	60-130	88.32	Goettl and Davies 1977
Rainbow trout, *Salmo gairdneri*	ELS	Sodium selenite	135	>47[d]	>47	Hodson et al. 1980
Fathead minnow, *Pimephales promelas*	ELS	Selenious acid	220[c]	83-153	112.7	Kimball, Manuscript
Selenium(VI)						
Cladoceran, *Daphnia magna*	LC	Sodium selenate	129.5	1,730-2,310	1,999	Dunbar et al. 1983
Rainbow trout, *Salmo gairdneri*	ELS	Sodium selenate	45	2,200-3,800	2,891	Spehar 1986
Fathead minnow, *Pimephales promelas*	ELS	Sodium selenate	45-47	390-820	565.5	Spehar 1986

Table 2. (continued)

Species	Test[a]	Chemical	Salinity (g/kg)	Chronic limits (µg/L)[b]	Chronic Value (µg/L)	Reference
SALTWATER SPECIES						
Selenium(IV)						
Mysid, *Mysidopsis bahia*	LC	Selenious acid	26	140-320	211.7	U.S. EPA 1978; Ward et al. 1981
Sheepshead minnow, *Cyprinodon variegatus*	ELS	Sodium selenite	27	470-970	675.2	Ward et al. 1981

[a] LC = life-cycle or partial life-cycle; ELS = early life-stage.

[b] Measured concentrations of selenium.

[c] From Smith et al. (1976).

[d] None of the tested concentrations caused effects that were considered unacceptable.

Acute-Chronic Ratio

Species	Hardness (mg/L as $CaCO_3$)	Acute Value (µg/L)	Chronic Value (µg/L)	Ratio
Selenium(IV)				
Cladoceran, *Daphnia magna*	220	1,220	91.65	13.31
Cladoceran, *Daphnia pulex*	46.4	3,870	692.8	5.586

Table 2. (continued)

Species	Hardness (mg/L as $CaCO_3$)	Acute Value (µg/L)	Chronic Value (µg/L)	Ratio
Rainbow trout, *Salmo gairdneri*	30	12,500	88.32	141.5
Rainbow trout, *Salmo gairdneri*	135	8,800	>47	<187.2
Fathead minnow, *Pimephales promelas*	220	775.5[a]	112.7	6.881
Mysid, *Mysidopsis bahia*	26[b]	1,500	211.7	7.085
Sheepshead minnow, *Cyprinodon variegatus*	27[b]	7,400	675.2	10.96
		Selenium(VI)		
Cladoceran, *Daphnia magna*	129.5	5,300	1,999	2.651
Rainbow trout, *Salmo gairdneri*	45	47,000	2,891	16.26
Fathead minnow, *Pimephales promelas*	45-47	5,500	565.5	9.726

[a] Geometric mean of two values in Table 1.

[b] Salinity (g/kg), not hardness.

Table 3. Ranked Genus Mean Acute Values with Species Mean Acute-Chronic Ratios

Rank[a]	Genus Mean Acute Value (µg/L)	Species	Species Mean Acute Value (µg/L)[b]	Species Mean Acute-Chronic Ratio[c]
		FRESHWATER SPECIES		
		Selenium(IV)		
22	203,000	Leech, *Nephelopsis obscura*	203,000	-
21	42,500	Midge, *Tanytarsus dissimilis*	42,500	-
20	35,000	Common carp, *Cyprinus carpio*	35,000	-
19	34,910	Snail, *Aplexa hypnorum*	34,910	-
18	30,180	White sucker, *Catostomus commersoni*	30,180	-
17	28,500	Bluegill, *Lepomis macrochirus*	28,500	-
16	26,100	Goldfish, *Carassius auratus*	26 100	-
15	25,930	Midge, *Chironomus plumosus*	25,930	-
14	24,100	Snail, *Physa* sp.	24,100	-

Table 3. (continued)

Rank[a]	Genus Mean Acute Value (µg/L)	Species	Species Mean Acute Value (µg/L)[b]	Species Mean Acute-Chronic Ratio[c]
13	13,600	Channel catfish, *Ictalurus punctatus*	13,600	-
12	12,600	Mosquitofish, *Gambusia affinis*	12,600	-
11	11,700	Yellow perch, *Perca flavescens*	11,700	-
10	10,490	Rainbow trout, *Salmo gairdneri*	10,490	141.5
9	10,200	Brook trout, *Salvelinus fontinalis*	10,200	-
8	6,500	Flagfish, *Jordanella floridae*	6,500	-
7	2,704	Amphipod, *Gammarus pseudolimnaeus*	2,704	-
6	1,820	Cladoceran, *Daphnia magna*	855.8	13.31
		Cladoceran, *Daphnia pulex*	3,870	5.586
5	1,783	Striped bass, *Morone saxatilis*	1,783	-

Table 3. (continued)

Rank[a]	Genus Mean Acute Value (µg/L)	Species	Species Mean Acute Value (µg/L)[b]	Species Mean Acute-Chronic Ratio[c]
4	1,700	Hydra, *Hydra* sp	1,700	-
3	1,601	Fathead minnow, *Pimephales promelas*	1,601	6.881
2	<603.6	Cladoceran, *Ceriodaphnia affinis*	<603.6	-
1	340	Amphipod, *Hyalella azteca*	340	-
		Selenium(VI)		
11	442,000	Leech, *Nephelopsis obscura*	442,000	-
10	193,000	Snail, *Aplexa hypnorum*	193,000	-
9	66,000	Channel catfish, *Ictalurus punctatus*	66,000	-
8	63,000	Bluegill, *Lepomis macrochirus*	63,000	-
7	47,000	Rainbow trout, *Salmo gairdneri*	47,000	16.26

Table 3. (continued)

Rank[a]	Genus Mean Acute Value (µg/L)	Species	Species Mean Acute Value (µg/L)[b]	Species Mean Acute-Chronic Ratio[c]
6	20,000	Midge, *Paratanytarsus parthenogeneticus*	20,000	-
5	7,300	Hydra, *Hydra* sp.	7,300	-
4	5,500	Fathead minnow, *Pimephales promelas*	5,500	9.726
3	760	Amphipod, *Hyalella azteca*	760	-
2	597.2	Cladoceran, *Daphnia magna*	1,450	2.651
		Cladoceran, *Daphnia pulicaria*	246	-
1	65.38	Amphipod, *Gammarus pseudolimnaeus*	65.38	-

Table 3. (continued)

Rank[a]	Genus Mean Acute Value (µg/L)	Species	Species Mean Acute Value (µg/L)[b]	Species Mean Acute-Chronic Ratio[c]
		SALTWATER SPECIES		
		Selenium (IV)		
15	17,350	Fourspine stickleback, *Apeltes quadracus*	17,350	-
14	14,650	Winter flounder, *Pseudopleuronectes americanus*	14,650	-
13	>10,000	Blue mussel, *Mytilus edulis*	>10,000	-
12	>10,000	Pacific oyster, *Crassostrea gigas*	>10,000	-
11	9,725	Atlantic silverside, *Menidia menidia*	9,725	-
10	7,400	Sheepshead minnow, *Cyprinodon variegatus*	7,400	10.96
9	4,600	Blue crab, *Callinectes sapidus*	4,600	-
8	4,400	Pinfish, *Lagodon rhomboides*	4,400	-

Table 3. (continued)

Rank[a]	Genus Mean Acute Value (µg/L)	Species	Species Mean Acute Value (µg/L)[b]	Species Mean Acute-Chronic Ratio[c]
7	3,497	Summer flounder, *Paralichthys dentatus*	3,497	-
6	1,550	Striped bass, *Morone saxatilis*	1,550	-
5	1,500	Mysid, *Mysidopsis bahia*	1,500	7.085
4	1,330	Copepod, *Acartia clausi*	2,110	-
		Copepod, *Acartia tonsa*	839	-
3	1,200	Brown shrimp, *Penaeus aztecus*	1,200	-
2	1,040	Dungeness crab, *Cancer magister*	1,040	-
1	599	Haddock, *Melanogrammus aeglefinus*	599	-

[a] Ranked from most resistant to most sensitive based on Genus Mean Acute Value. Inclusion of "greater than" and "less than" values does not necessarily imply a true ranking, but does allow use of all genera for which data are available so that the Final Acute Value is not unnecessarily lowered.

[b] From Table 1.

[c] From Table 2.

Table 3. (continued)

Selenium(IV)

Fresh water

Final Acute Value = 371.8 µg/L

Criterion Maximum Concentration = (371.8 µg/L) / 2 = 185.9 µg/L

Final Acute-Chronic Ratio = 8.314 (see text)

Final Chronic Value = (371.8 µg/L) / 8.314 = 44.72 µg/L

Final Chronic Value = 27.6 µg/L (lowered to protect rainbow trout, see text)

Salt water

Final Acute Value = 587.7 µg/L

Criterion Maximum Concentration = (587.7 µg/L) / 2 = 293.8 µg/L

Final Acute-Chronic Ratio = 8.314 (see text)

Final Chronic Value = (587.7 µg/L) / 8.314 = 70.69 µg/L

Selenium(VI)

Fresh water

Final Acute Value = 25.65 µg/L

Criterion Maximum Concentration = (25.65 µg/L) / 2 = 12.82 µg/L

Final Acute-Chronic Ratio = 2.651 (see text)

Final Chronic Value = (25.65 µg/L) / 2.651 = 9.676 µg/L

Table 4. Toxicity of Selenium to Aquatic Plants

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration ($\mu g/L$)[a]	Reference
			FRESHWATER SPECIES			
			Selenium(IV)			
Green alga, Chlorella vulgaris	Sodium selenite	-	90-120	Reduced growth	5,480	De Jong 1965
Green alga, Scenedesmus dimorphus	Sodium selenite	-	14	Reduced growth	24,000	Woede et al. 1980
Green alga, Scenedesmus quadricauda	Sodium selenite	-	8	Incipient inhibition	522	Bringmann and Kuhn 1977a,1978a,b;1979; 1980b
Green alga, Scenedesmus quadricauda	Sodium selenite	-	8	Incipient inhibition	2,500	Bringmann and Kuhn 1959a
Blue-green alga, Microcystis aeruginisa	Sodium selenite	-	8	Incipient inhibition	9,400 (9,3[illegible]	Bringmann and Kuhn 1976;1978a,b
Blue-green alga, Anabaena cylindrica	Sodium selenite	-	14	Reduced growth	24,000	Woede et al. 1980
Blue-green alga, Anabaena variabilis	Sodium selenite	-	6-18	LC50	15,000[b]	Kumar and Prakash 1971
Blue-green alga, Anacystis nidulans	Sodium selenite	-	10-18	LC50	30,000[b]	[illegible]r and Prakash 1971
Green alga, Selenastrum capricornutum	Sodium selenite	-	4	EC50	2,900	Richter 1982

Table 4. (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)[a]	Reference
Alga, *Euglena gracilis*	-	-	15	Reduced growth	5,920	Bariaud and Westre 1984
Duckweed, *Lemna minor*	-	-	4	EC50	2,400	Wang 1986
				Selenium(VI)		
Blue-green alga, *Anabaena cylindrica*	Sodium selenate	-	14	Reduced growth	22,100	Woede et al. 1980
Blue-green alga, *Microcoleus vaginatus*	Sodium selenate	-	14	Reduced growth	10,000	Vocke et al. 1980
Green alga, *Ankistrodesmus falcatus*	Sodium selenate	-	14	Did not reduce growth	10	Vocke et al. 1980
Green alga, *Scenedesmus dimorphus*	Sodium selenate	-	14	Reduced growth	22,100	Woede et al. 1980
Green alga, *Scenedesmus obliquus*	Sodium selenate	-	14	Reduced growth	100	Vocke et al. 1980
Green alga, *Selenastrum capricornutum*	Sodium selenate	-	14	Reduced growth	300	Vocke et al. 1980

Table 4. (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)[a]	Reference
Green alga, *Selenastrum capricornutum*	Sodium selenate	-	4	EC50	199	Richter 1982
Blue-green alga, *Anacystis nidulans*	Sodium selenate	-	6-18	EC50	39,000[b]	Kumar and Prakash 1971
Blue-green alga, *Anabaena*	Sodium selenate	-	10-18	EC50	17,000[b]	Kumar and Prakash 1971
SALTWATER SPECIES						
Selenium(VI)						
Diatom, *Skeletonema costatum*	Selenious acid[c]	-	4	EC50 (reduction in chlorophyll a)	7,930	U.S. EPA 1978
Dinoflagellate, *Peridinopsis borgei*	Selenium oxide	-	70-75	Maximum growth	0.01-0.05	Lindstrom 1985

[a] Concentration of selenium, not the chemical.

[b] Estimated from published graph.

[c] Reported by Barrows et al. (1980) in work performed under the same contract.

Table 5. Bioaccumulation of Selenium by Aquatic Organisms

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Concentration in Water (µg/L)[a]	Duration (days)	Tissue	BCF or BAF[b]	Reference
			FRESHWATER SPECIES				
			Selenium(IV)				
Rainbow trout, *Salmo gairdneri*	Sodium selenite	325	-	48	Muscle	2	Adams 1976
Rainbow trout, *Salmo gairdneri*	Sodium selenite	325	-	48	Whole body	10[c]	Adams 1976
Rainbow trout (embryo), *Salmo gairdneri*	Sodium selenite	135	-	308 (post hatch)	Whole body (estimate)	8	Hodson et al. 1980
Fathead minnow, *Pimephales promelas*	Sodium selenite	320-360	-	96	Muscle	11.6	Adams 1976
Fathead minnow, *Pimephales promelas*	Sodium selenite	320-360	-	96	Whole body	17.6	Adams 1976
Bluegill, *Lepomis macrochirus*	Selenious acid	-	-	28	Whole body	20	Barrows et al. 1980
Bluegill, *Lepomis macrochirus*	Sodium selenite	25	10	120	Whole body	450	Lemly 1982
		25	10	120	Whole body	470	
		200	10	120	Whole body	430	
		200	10	120	Whole body	460	
Largemouth bass, *Micropterus salmoides*	Sodium selenite	25	10	120	Whole body	310	Lemly 1982
		25	10	120	Whole body	300	
		200	10	120	Whole body	300	
		200	10	120	Whole body	270	

Table 5. (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Concentration in Water (µg/L)[a]	Duration (days)	Tissue	BCF or BAF[b]	Reference
			Selenium VI				
Fathead minnow (6-9 mo), Pimephales promelas	Sodium selenate	-	10 7	56	Whole body	52[d]	Bertram and Brooks 1986
Fathead minnow (6-9 mo), Pimephales promelas	Sodium selenate	-	21 5	56	Whole body	26[d]	Bertram and Brooks 1986
Fathead minnow (6-9 mo), Pimephales promelas	Sodium selenate	-	43 5	56	Whole body	21[d]	Bertram and Brooks 1986
			SALTWATER SPECIES				
			Selen[illegible]				
Euphausiid (adult), Meganyctiphanes norvegica	Sodium selenite	-	-	28	Whole animal	200	Fowler and Benayoun 1976c
Euphausiid (adult), Meganyctiphanes norvegica	Sodium selenite	-	-	28	Whole animal	800[e]	Fowler and Benayoun 1976c
Shore crab (adult), Carcinus maenas	Sodium selenite	-	250	29	Gill	14.40[f]	Bjerregaard 1982
Shore crab (adult), Carcinus maenas	Sodium selenite	-	250	29	Hepato-pancreas	4.080[f,g]	Bjerregaard 1982
Shore crab (adult), Carcinus maenas	Sodium selenite	-	250	29	Muscle	2.880[f,g]	Bjerregaard 1982

Table 5. (continued)

Species	Chemical	Salinity (g/kg)	Concentration in Water (µg/L)[a]	Duration (days)	Tissue	BCF or BAF[b]	Reference
			Selenium VI				
Striped bass (juvenile, fed), Morone saxatilis	Sodium selenate	-	90	60	Whole body	No Increase	Klauda 1985
Striped bass (juvenile, starved), Morone saxatilis	Sodium selenate	-	90	60	Whole body	11.78	Klauda 1985
Striped bass (juvenile, fed), Morone saxatilis	Sodium selenate	-	1,290	60	Whole body	0.68	Klauda 1985
Striped bass (juvenile, starved), Morone saxatilis	Sodium selenate	-	1,290	60	Whole body	0.69	Kauda 1985

[a] Measured concentration of selenium.

[b] Bioconcentration factors (BCFs) and bioaccumulation factors (BAFs) are based on measured concentrations of selenium in water and in tissue.

[c] Estimated from graph.

[d] Calculated by dividing the reported equilibrium concentration in tissue (steady-state body burden) by the average measured concentration in water.

[e] Includes uptake from food.

[f] Factor was converted from dry weight to wet weight basis (see Guidelines).

[g] Concentration of selenium was the same in exposed and control animals.

Table 6. Other Data on Effects of Selenium on Aquatic Organisms

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration ($\mu g/L$)[a]	Reference
			FRESHWATER SPECIES			
			Selenium(IV)			
Green alga, Scenedesmus quadricauda	Sodium selenite	-	96 hr	Incipient inhibition (river water)	2,500	Bringmann and Kuhn 1959a,b
Green alga, Selenastrum capricornutum	Sodium selenite	-	72 hr	Decreased dry weight and chlorophyll a	75	Foe and Knight, Manuscript
Green alga, Selenastrum capricornutum	Sodium selenite	-	72 hr	BCF = 12-21[b]	10-100	Foe and Knight, Manuscript
Green alga, Selenastrum capricornutum	Sodium selenite	-	72 hr	BCF = 11,164[c]	150	Foe and Knight, Manuscript
Alga, Chrysochromulina breviturrita	Selenious acid	-	30 days	Increased growth	320	Wehr and Brown 1985
Algae (diatoms), Mixed population	Sodium selenite	-	18 days	Inhibited growth	11,000	Patrick et al. 1975
Bacterium, Escherichia coli	Sodium selenite	-	-	Incipient inhibition	90,000	Bringmann and Kuhn 1959a
Bacterium, Pseudomonus putida	Sodium selenite	-	16 hr	Incipient inhibition	11,400 (11,200)	Bringmann and Kuhn 1976;1977a;1979;1980b

Table 6. (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration ($\mu g/L$)[a]	Reference
Protozoan, *Entosiphon sulcatum*	Sodium selenite	-	72 hr	Incipient inhibition	1.8 (1.9)	Bringmann 1978; Bringmann and Kuhn 1979;1980b;1981
Protozoan, *Microregma heterostoma*	Sodium selenite	-	28 hr	Incipient inhibition	183,000	Bringmann and Kuhn 1959b
Protozoan, *Chilomonas paramecium*	Sodium selenite	-	48 hr	Incipient inhibition	62	Bringmann and Kuhn 1981; Bringmann et al. 1980
Protozoan, *Uronema parduezi*	Sodium selenite	-	20 hr	Incipient inhibition	118	Bringmann and Kuhn 1980a,1981
Snail, *Lymnaea stagnalis*	Sodium selenite	-	7.5 days	LT50	3,000	Van Puymbroeck et al. 1982
Cladoceran, *Daphnia magna*	Sodium selenite	-	48 hr	EC50 (river water)	2,500	Bringmann and Kuhn 1959a,b
Cladoceran, *Daphnia magna*	Sodium selenite	214	24 hr	LC50	16,000	Bringmann and Kuhn 1977a
Cladoceran, *Daphnia magna*	Sodium selenite	214	24 hr	EC50 (swimming)	9.9	Bringmann and Kuhn 1977b
Cladoceran, *Daphnia magna*	Sodium selenite	329	48 hr 96 hr 14 days	EC50 (fed)	710 430 430	Halter et al. 1980

Table 6. (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration ($\mu g/L$)[a]	Reference
Cladoceran (<24 hr), *Daphnia magna*	Sodium selenite	-	48 hr 21 days	EC50 (fed)	685 160	Adams and Heidolph 1985
Cladoceran, *Daphnia magna*	Selenious acid	220[d]	48 hr	LC50 (fed)	1,200	Kimball, Manuscript
Ostracod, *Cyclocypris* sp.	Sodium selenite	100 8	48 hr	LC50	130,000	Owsley 1984
Amphipod, *Hyalella azteca*	Sodium selenite	329	14 days	LC50 (fed)	70	Halter et al. 1980
Coho salmon (fry), *Oncorhynchus kisutch*	Sodium selenite	325	43 days	LC50	160	Adams 1976
Rainbow trout (fry), *Salmo gairdneri*	Sodium selenite	334	21 days	LC50	460	Adams 1976
Rainbow trout (fry), *Salmo gairdneri*	Sodium selenite	334	21 days	Reduced growth	250	Adams 1976
Rainbow trout, *Salmo gairdneri*	Sodium selenite	330	5 days	LC50	2,700 2,750	Adams 1976
Rainbow trout, *Salmo gairdneri*	Sodium selenite	325	48 days	LC50	500	Adams 1976
Rainbow trout, *Salmo gairdneri*	Sodium selenite	325	96 days	LC50	280	Adams 1976

Table 6. (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)[a]	Reference
Rainbow trout, *Salmo gairdneri*	Sodium selenite	135	9 days	LC50	7,020	Hodson et al. 1980
Rainbow trout, *Salmo gairdneri*	Sodium selenite	135	96 hr 9 days	LC50 (fed)	7,200 5,410	Hodson et al. 1980
Rainbow trout, *Salmo gairdneri*	Sodium selenite	135	96 hr 9 days	LC50 (fed)	8,200 6,920	Hodson et al. 1980
Rainbow trout, *Salmo gairdneri*	Sodium selenite	135	41 days	Reduced hatch of eyed embryos	47	Hodson et al. 1980
Rainbow trout, *Salmo gairdneri*	Sodium selenite	135	50 wk	Decreased iron in blood	53	Hodson et al. 1980
Rainbow trout (embryo), *Salmo gairdneri*	Sodium selenite	-	120 hr	Did not reduce survival or time to hatch	10,000	Klaverkamp et al. 1983b
Rainbow trout, *Salmo gairdneri*	Sodium selenite	272	90 days	LC50	55.2[e]	Hunn et al. 1987
Northern pike, *Esox lucius*	Sodium selenite	10.2	76 hr	LC50	11,100	Klaverkamp et al. 1983a
Goldfish, *Carassius auratus*	Selenium dioxide	157	14 days	LC50	6,300	Cardwell et al. 1976a,b

Table 6. (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)[a]	Reference
Goldfish, *Carassius auratus*	Sodium selenite	-	10 days	Mortality	5,000	Ellis 1937; Ellis et al. 1937
Goldfish, *Carassius auratus*	Sodium selenite	-	46 days	Gradual anorexia and mortality	2,000	Ellis et al. 1937
Goldfish, *Carassius auratus*	Selenium dioxide	-	7 days	LC50	12,000	Weir and Hine 1970
Goldfish, *Carassius auratus*	Selenium dioxide	-	48 hr	Conditional avoidance	250	Weir and Hine 1970
Goldfish, *Carassius auratus*	Sodium selenate	-	24 hr	BCF = 1.42 BCF = 1.15 BCF = 1.47 BCF = 0.88 BCF = 1.54	0.45 0.9 1.35 2.25 4.5	Sharma and Davis 1980
Fathead minnow, *Pimephales promelas*	Sodium selenate	338	48 days	LC50	1,100	Adams 1976
Fathead minnow, *Pimephales promelas*	Selenium dioxide	157	9 days	LC50	2,100	Cardwell et al. 1976a,b
Fathead minnow, *Pimephales promelas*	Sodium selenite	329	96 hr	LC50 (fed)	1,000	Halter et al. 1980
Fathead minnow, *Pimephales promelas*	Sodium selenite	329	14 days	LC50 (fed)	600	Halter et al. 1980
Fathead minnow, *Pimephales promelas*	Selenious acid	220[d]	8 days	LC50 (fed)	420	Kimball, Manuscript

Table 6. (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)[a]	Reference
Creek chub, *Semotilus atromaculatus*	Selenium dioxide	-	48 hr	Mortality	≥12,000	Kim et al. 1977
Bluegill, *Lepomis macrochirus*	Sodium selenite	318	48 days	LC50	400	Adams 1976
Bluegill, *Lepomis macrochirus*	Selenium dioxide	157	14 days	LC50	12,500	Cardwell et al. 1976a,b
Yellow perch, *Perca flavescens*	Sodium selenite	10.2	10 days	LC50	4,800	Klaverkamp et al. 1983
African clawed frog, *Xenopus laevis*	Sodium selenite	-	7 days	LC50	1,520	Browne and Dumont 1979
African clawed frog, *Xenopus laevis*	Sodium selenite	-	1-7 days	Cellular damage	2,000	Browne and Dumont 1980
			Selenium(VI)			
Alga, *Chrysochromulina breviturrita*	-	-	30 days	Increased growth	50	Wehr and Brown 1985
Snail, *Lymnaea stagnalis*	Sodium selenate	-	6 days	LT50	15,000	Van Puymbroeck et al. 1982
Cladoceran, *Daphnia magna*	Sodium selenate	129.5	7 days	LC50 (fed)	1,870	Dunbar et al. 1983

Table 6. (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)[a]	Reference
Rainbow trout (embryo, larva), *Salmo gairdneri*	Sodium selenate	104 (92-110)	28 days	EC50 (death and deformity)	5,000 (4,180) (5,170)	Birge 1978; Birge and Black 1977; Birge et al. 1980
Goldfish (embryo, larva), *Carassius auratus*	Sodium selenate	195	7 days	EC50 (death and deformity)	8,780	Birge 1978
Fathead minnow, *Pimephales promelas*	Sodium selenate	337.9	48 days	LC50	2,000	Adams 1976
Fathead minnow, *Pimephales promelas*	-	51	30 min	No avoidance	11,200	Watenpaugh and Beitinger 1985a
Fathead minnow, *Pimephales promelas*	-	-	24 hr	LC50	82,000	Watenpaugh and Beitinger 1985b
Fathead minnow, *Pimephales promelas*	-	-	24 hr	Reduced thermal tolerance	22,200	Watenpaugh and Beitinger 1986c
Channel catfish (embryo, fry), *Ictalurus punctatus*	Sodium selenate	90	8 5-9 days	Induced albinism	-	Westerman and Birge 1978
Narrow-mouthed toad (embryo, larva), *Gastrophryne carolinensis*	Sodium selenate	195	7 days	EC50 (death and deformity)	90	Birge 1978; Birge and Black 1977; Birge et al. 1979a

Table 6. (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)[a]	Reference
			SALTWATER SPECIES			
			Selenium(IV)			
Anaerobic bacterium, *Methanococcus vannielli*	Sodium selenite	-	110 hr	Stimulated growth	79 01	Jones and Stadtman 1977
Green alga, *Chlorella* sp	Sodium selenite	32	14 days	5-12% increase in growth	10-10,000	Wheeler et al 1982
Green alga, *Platymonas subcordiformis*	Sodium selenite	32	14 days	23% increase in growth	100-10,000	Wheeler et al 1982
Green alga, *Dunaliella primolecta*	Sodium selenite	32	20 days	Increased growth, induced glutathione peroxidase	4,600	Gennity et al 1985a,b
Diatom, *Thallassiosira aestivalis*	Selenium oxide	29-30	72 hr	No effect on cell morphology	78 96	Thomas et al 1980a
Brown alga, *Fucus spiralis*	Sodium selenite	-	60 days	1355% increase in growth of thalli	2 605	Fries 1982
Red alga, *Porphyridium cruentum*	Sodium selenite	32	27 days	Increase growth, induced glutathione peroxidase	4,600	Gennity et al 1985a,b

Table 6. (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)[a]	Reference
			Selenium(VI)			
Green alga, *Chlorella* sp	Sodium selenate	32	14 days	No effect on rate of cell	10-1000	Wheeler et al. 1982
Green alga, *Chlorella* sp	Sodium selenate	32	4-5 days	100% mortality	10,000	Wheeler et al. 1982
Green alga, *Dunaliella primolecta*	Sodium selenate	32	14 days	No effect on rate of cell population growth	10-100	Wheeler et al. 1982
Green alga, *Dunaliella primolecta*	Sodium selenate	32	14 days	71% reduction in rate of cell population growth	1,000	Wheeler et al. 1982
Green alga, *Dunaliella primolecta*	Sodium selenate	32	4-5 days	100% mortality	10,000	Wheeler et al. 1982
Green alga, *Platymonas subcordiformis*	Sodium selenate	32	14 days	No effect on rate of cell population growth	10	Wheeler et al. 1982
Green alga, *Platymonas subcordiformis*	Sodium selenate	32	14 days	16% decrease in rate of cell population growth	100	Wheeler et al. 1982
Green alga, *Platymonas subcordiformis*	Sodium selenate	32	14 days	50% decrease in rate of cell population growth	1,000	Wheeler et al. 1982

Table 6. (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)[a]	Reference
Green alga, *Platymonas subcordiformis*	Sodium selenate	32	4-5 days	100% mortality	10,000	Wheeler et al. 1982
Brown alga, *Fucus spiralis*	Sodium selenate	-	60 days	160% increase in growth rate of thalli	2,605	Fries 1982
Red alga, *Porphridium cruentum*	Sodium selenate	32	14 days	23-35% reduction in rate of cell population growth	10-1000	Wheeler et al. 1982
Red alga, *Porphyridium cruentum*	Sodium selenate	32	4-5 days	100% mortality	10,000	Wheeler et al. 1982
Eastern oyster (adult), *Crassostrea virginica*	Sodium selenate	34	14 days	No significant effect on respiration rate of gill tissue	400	Fowler et al. 1981
Striped bass (embryo), *Morone saxatilis*	Sodium selenate	7.2-7.5	4 days	93% successful hatch and survive	200,000	Klauda 1985
Striped bass (larva), *Morone saxatilis*	Sodium selenate	4.0-5.0	4 days	LC50 (control survival=77%)	13,020	Klauda 1985
Striped bass (juvenile), *Morone saxatilis*	Sodium selenate	3.5-5.5	9-65 days	Significant incidence of development anomalies of lower jaw	39-1,360	Klauda 1985

Table 6. (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/l)[e]	Reference
Striped bass (juvenile), *Morone saxatilis*	Sodium selenate	3.5-5.5	45 days	Significant incidence of severe blood cytopathology	1,290	Klauda 1985

[a] Concentration of selenium, not the chemical.

[b] Converted from dry weight to wet weight basis (see Guidelines).

[c] Growth of algae was inhibited.

[d] From Smith et al. (1976).

[e] Calculated from the published data using probit analysis and allowing for 8.9% spontaneous mortality.

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